Latest results on few-body physics from HIγS

8th International Workshop on Chiral Dynamics
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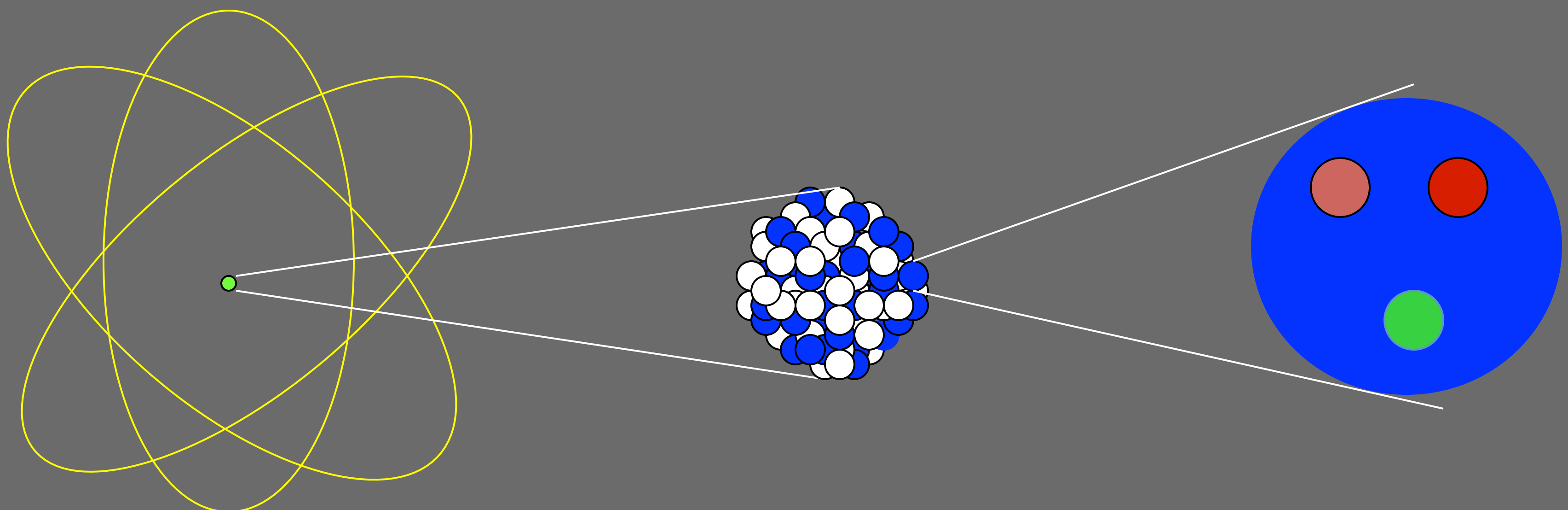
Outline

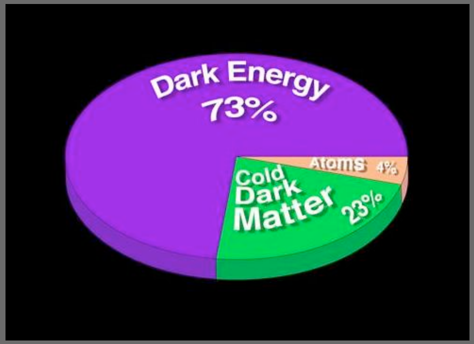
- Introduction
- Few-body systems
  - Important testing grounds for theories
  - important laboratory to probe the structure of the nucleon
- HIγS – unique facility
- Recent results on few-body system from HIγS
- Summary and outlook

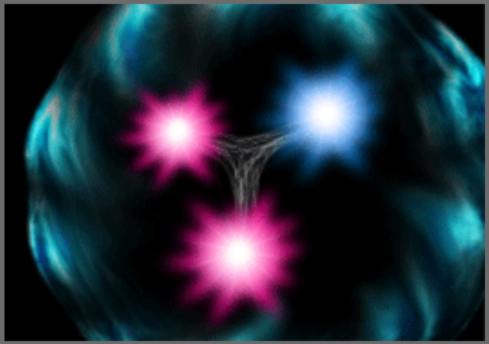
Nuclear physics is the study of the structure of matter

- Most of the mass and energy in the universe around us comes from nuclei and nuclear reactions.
- The nucleus is a unique form of matter in that all the forces of nature are present : (strong, electromagnetic, weak, and of course gravity).

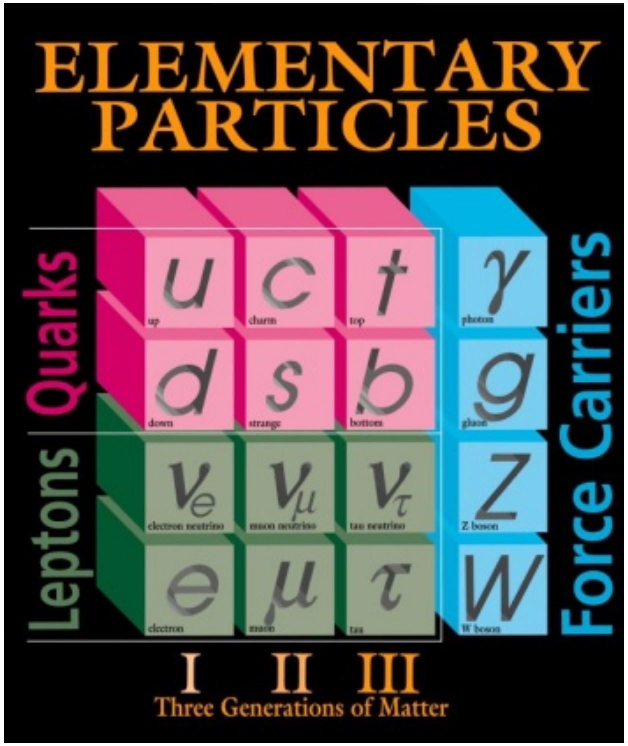


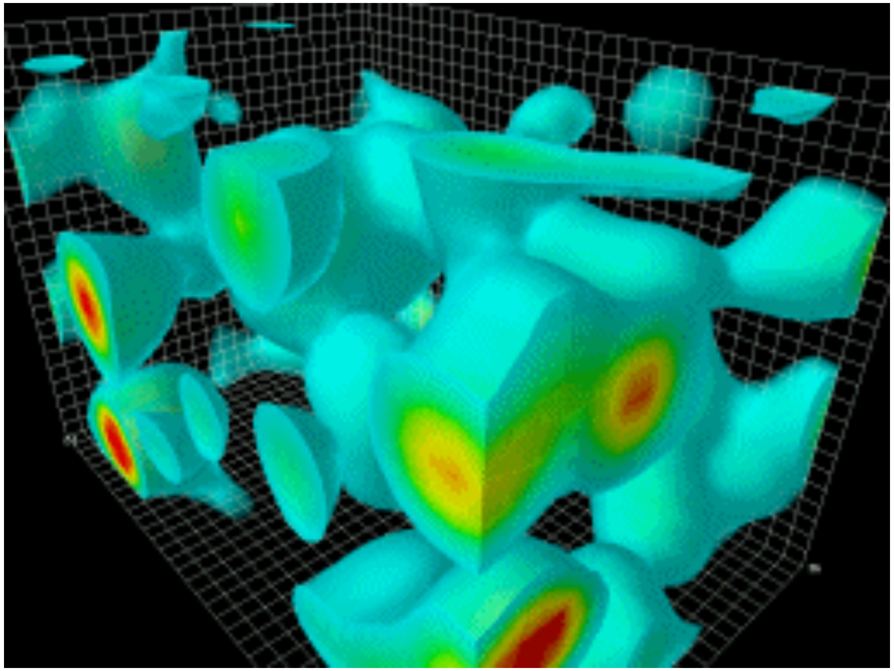
atom: **10^{-10} m** nucleus: **10^{-14} m** nucleon: **10^{-15} m**





Ultimate goal: Nuclear Physics from QCD





Gauge bosons: gluons (8)

- ***Non-pQCD remains challenging***
- ***Nucleon structure - important laboratory to study non-pQCD***
- ***Few-body systems provide effective neutron targets***
- ***A bridge between nucleon and heavier atomic nuclei***

What is inside the proton/neutron?

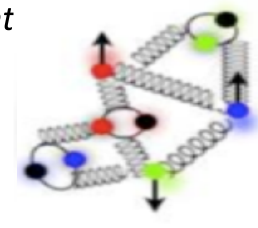
1933: Proton's magnetic moment

Nobel Prize
In Physics 1943

Otto Stern

"for … and for his discovery of the magnetic moment of the proton".

$g \neq 2$



1960: Elastic e-p scattering

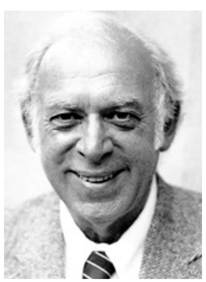
Nobel Prize
In Physics 1961

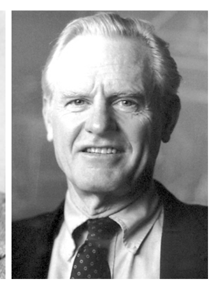
Robert Hofstadter

"for … and for his thereby achieved discoveries concerning the structure of the nucleons"

Form factors $\rightarrow$ Charge distributions

1969: Deep inelastic e-p scattering





Nobel Prize in Physics 1990

Jerome I. Friedman, Henry W. Kendall, Richard E. Taylor

"for their pioneering investigations concerning deep inelastic scattering of electrons on protons …".

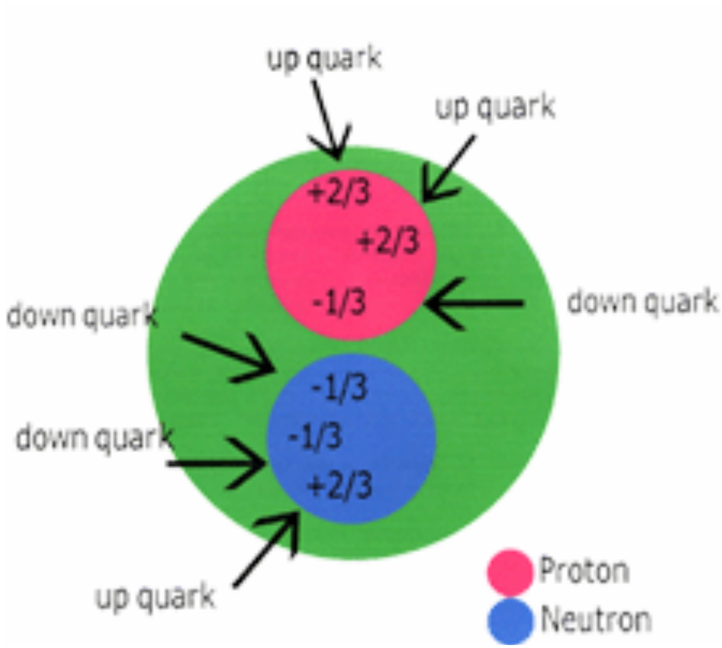
1974: QCD Asymptotic Freedom

Nobel Prize in Physics 2004

David J. Gross, H. David Politzer, Frank Wilczek

"for the discovery of asymptotic freedom in the theory of the strong interaction".

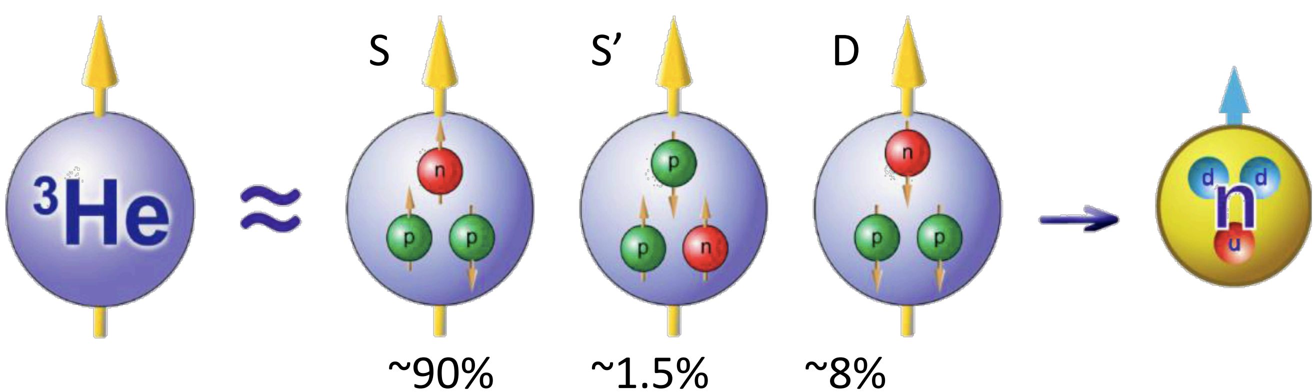
No Stable Free Neutron Targets



Effective neutron targets: Deuterium and ^{3}He used

Nuclear corrections needed

State-of-the-art calculations validated by experiments



QCD ⟷ *Nucleon Structure*

- Strong interaction, running coupling ~1

  -- QCD: the theory of strong interaction

  -- asymptotic freedom (2004 Nobel)

  perturbation calculation works at high energy

  -- interaction significant at intermediate energy

  quark-gluon correlations

  -- confinement

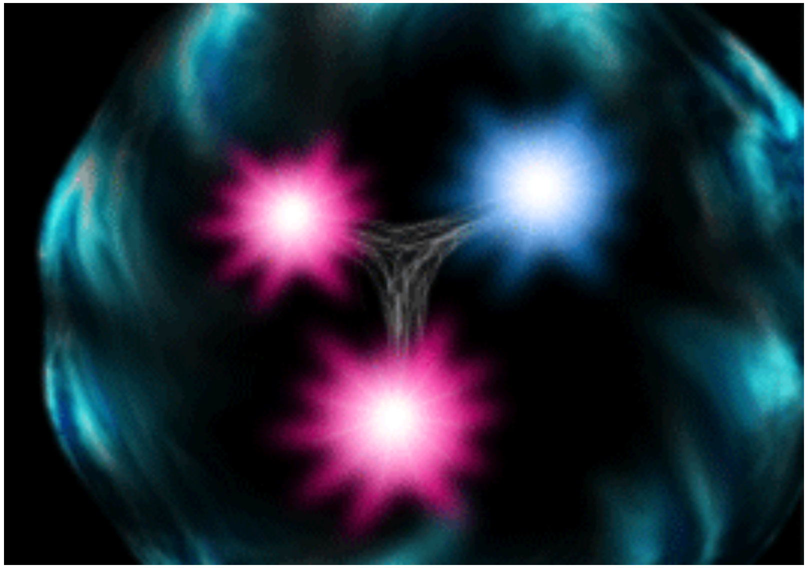
  interaction strong at low energy

  coherent hadron

  -- Chiral symmetry

  -- theoretical tools:

  pQCD, OPE, Lattice QCD, ChPT



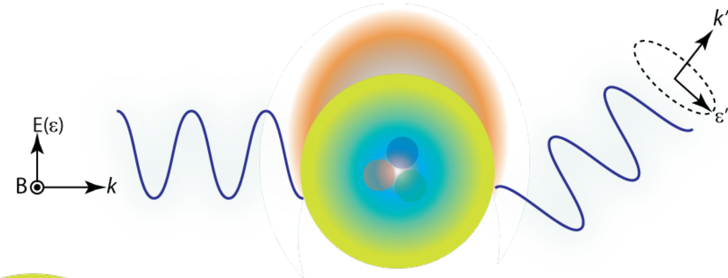
- *Charge and magnetism (current) distribution*
- *Spin distribution*
- *Quark momentum and flavor distribution*
- *Polarizabilities*
- *Strangeness content*
- *Three-dimensional structure*
- *……*

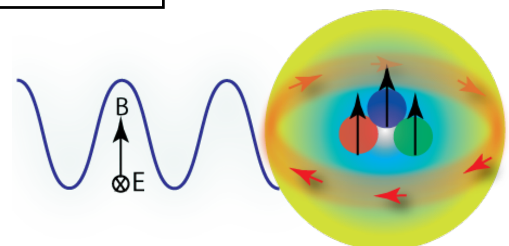
Spin as an important knob

Nucleon Polarizabilities

– EM Polarizabilities (α_E, β_M) : Response of a system to EM stimulus

$$\vec{p} = \alpha_E \vec{E}, \quad \vec{\mu} = \beta_M \vec{B}$$





– Spin Polarizabilities (γ_1, γ_2, γ_3, γ_4) : a measure of stiffness of the spin of the system

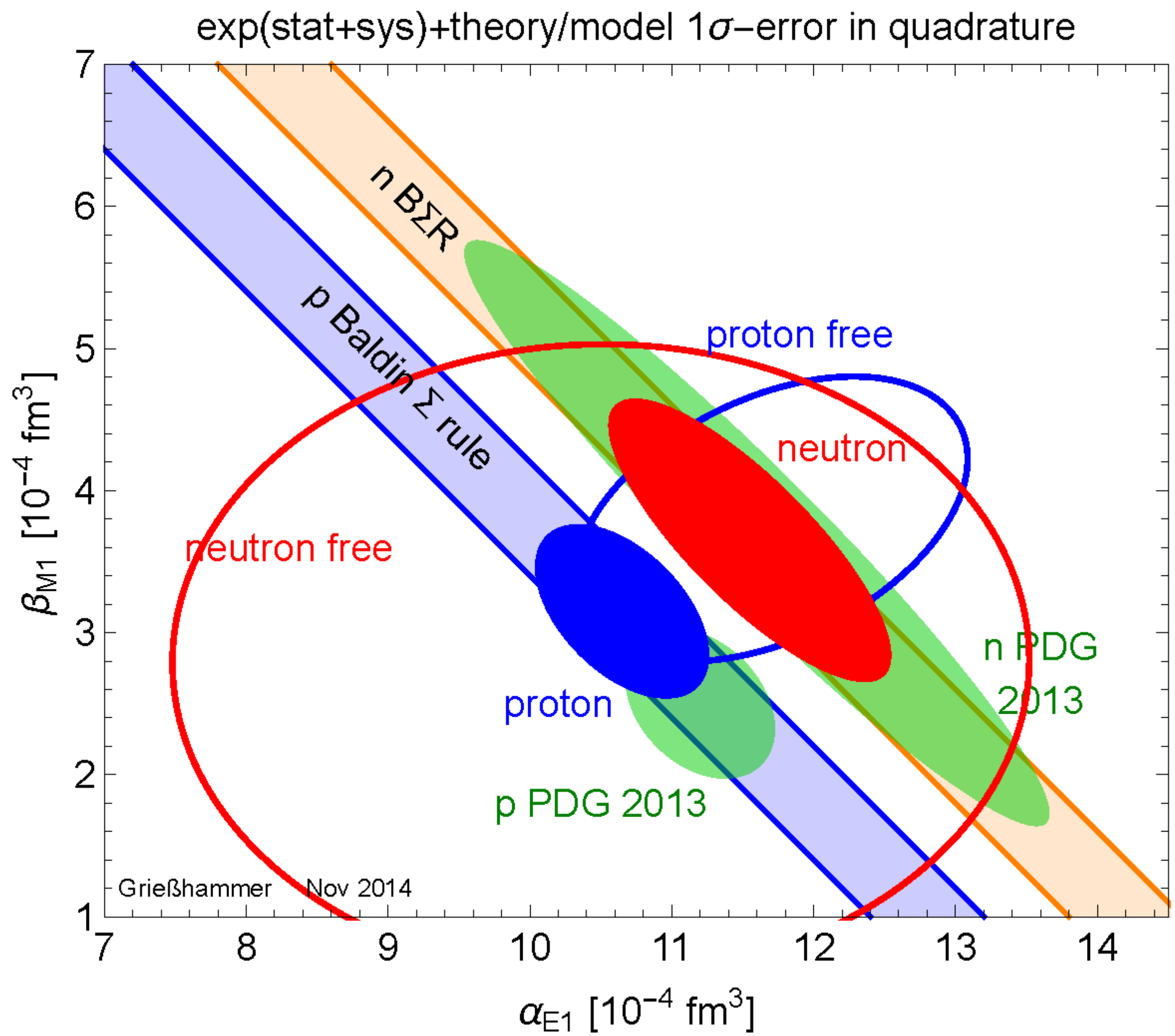
– Spin 1/2 target, there exists 4 independent spin polarizabilities (Ragusa)

$$\vec{p} = -\gamma_1 \vec{S} \times \frac{\partial \vec{E}}{\partial t}$$

$$\vec{p} = \gamma_3 \nabla(\vec{S} \bullet \vec{B})$$

Newest Data Set and State of the Affair (Deuteron)

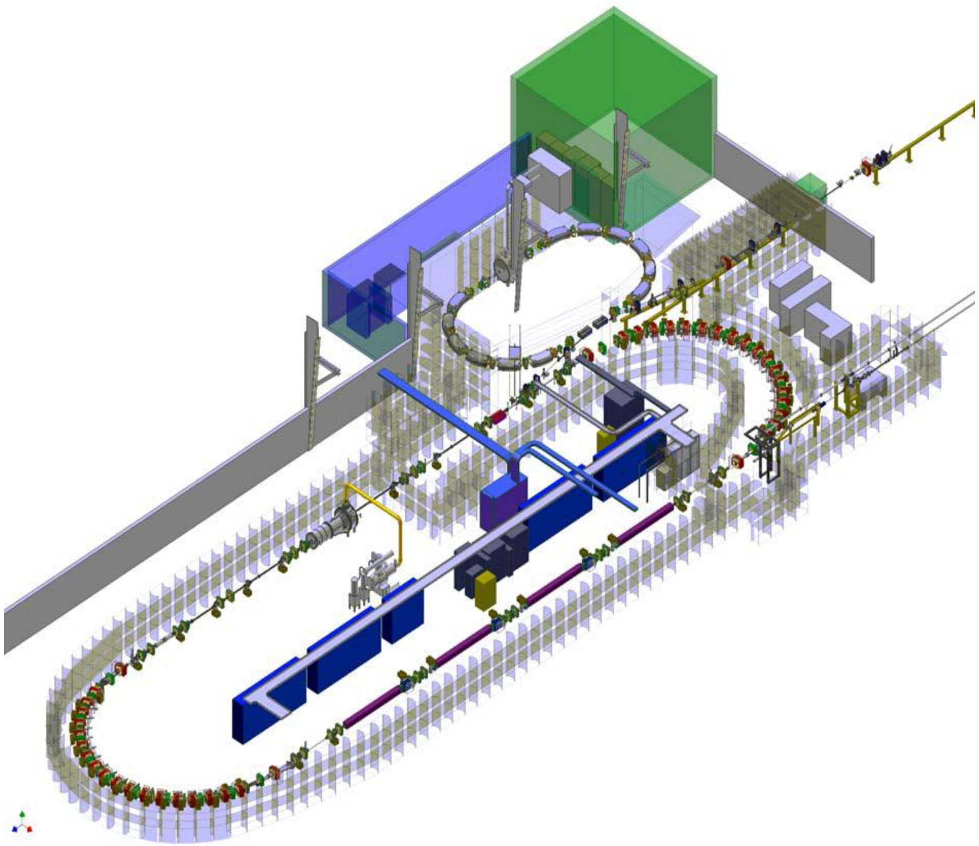
L. S. Myers,
PRL 113, 262506 (2014)



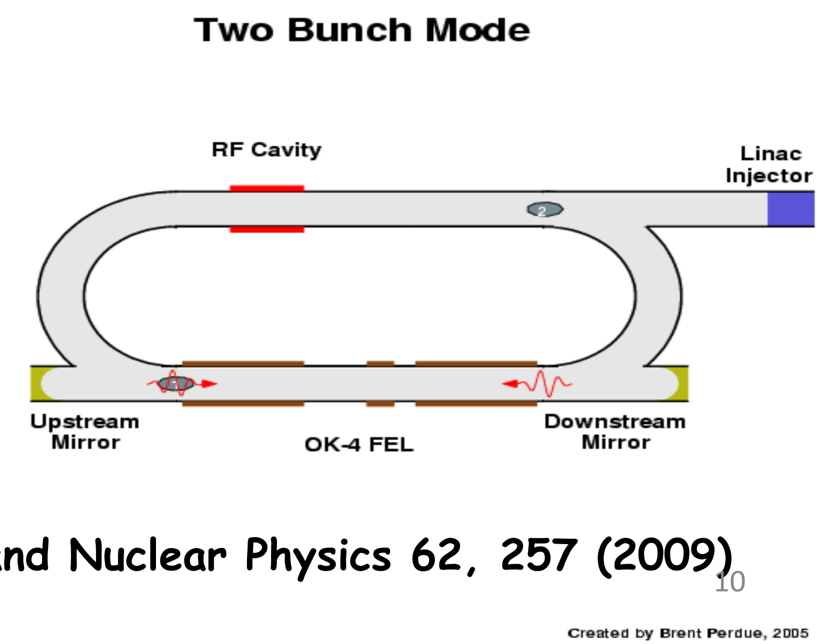
HWG, JAM, DRP, GF, PPNP, 67 (2012) 841-897, HG, Private Communication, 2015
JAM, DRP, HWG, EJP, A 49 (2013) 12

HIγS Facility at TUNL

Schematics of Duke Free Electron Laser



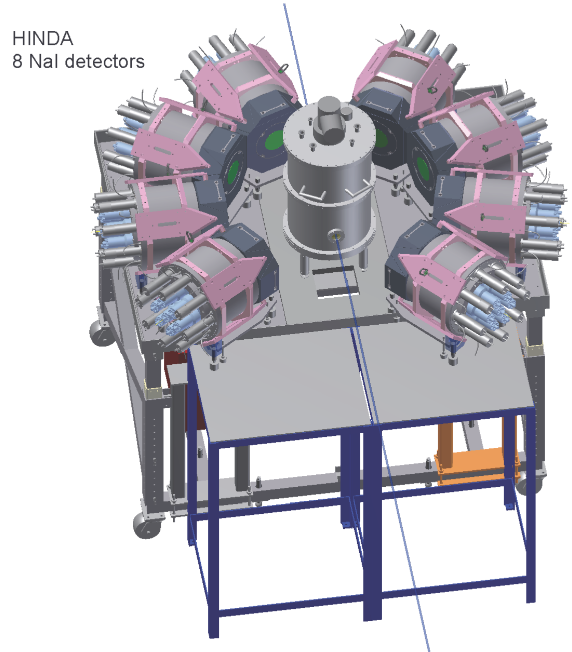
Beam Parameters	Values
Energies (MeV)	Up to 100 MeV
Polarization	~100 (circular or linear pol)



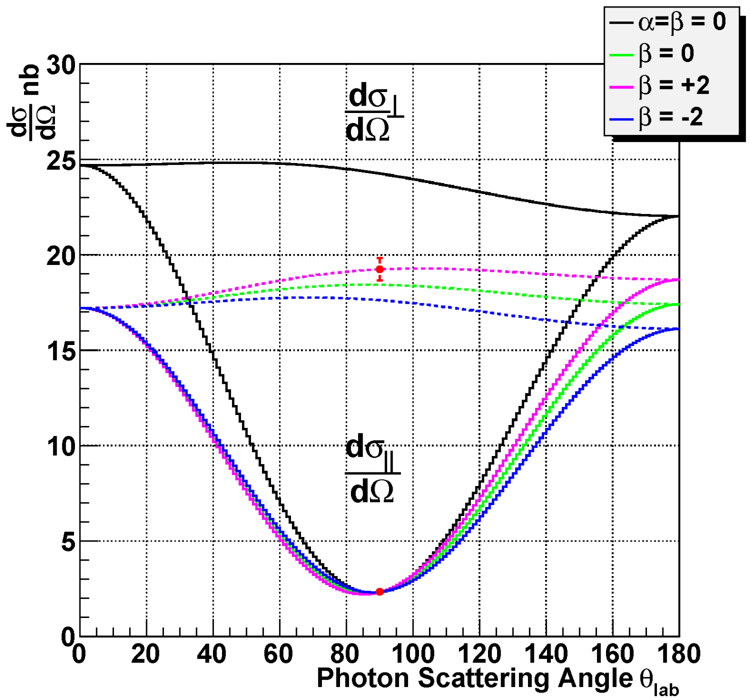
H.R. Weller *et al.*, Progress in Particle and Nuclear Physics 62, 257 (2009)

Measurements at HIGS (Proton)
First such measurement of alpha and beta separately

- Eγ = 85 MeV, Linearly Polarized
- Unpolarized LH Target
- Eight (8) 10 x 10 NaI with Active Shields (HINDA)
- Measure differential cross section and Asymmetry at 90°



Scattered photons attenuated < 5%

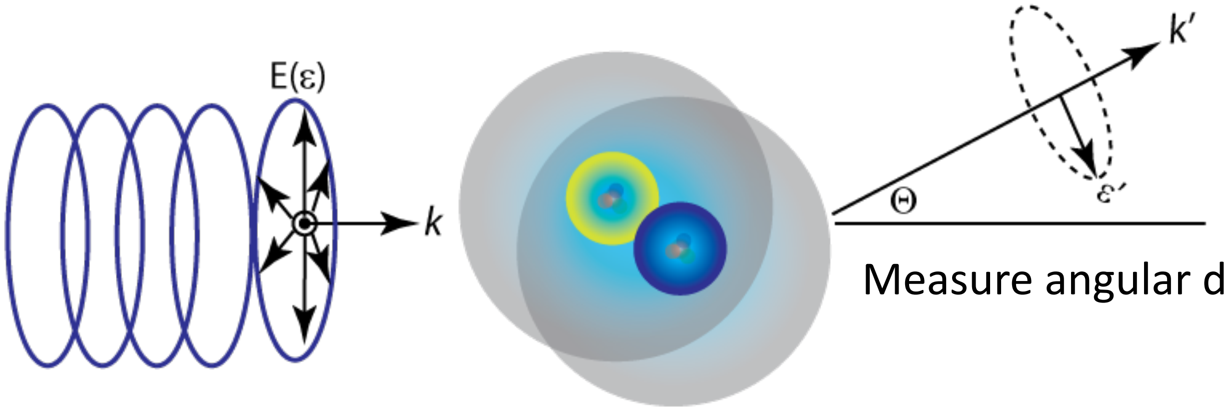


Quantity	Polarization	Eγ	% Err
α_p	Linear	85 MeV	2.5 %
β_p	Linear	85 MeV	<10%

M. Ahmed, H.R. Weller et al.

Measurements at HIGS (Deuteron)

65, 100 MeV,
Circularly Polarized



Measure angular distribution

Unpolarised LD target

Energy (MeV)	Angle	Cross Section (nb/sr)	Rate (counts/ hour)	Time (hours)	%Err (stat)
65	45	16.5	47	300	0.84%
65	80	12.4	36	300	0.96%
65	115	13.7	40	300	0.91%
65	150	17.8	52	300	0.80%

Will add 8 new points to the high-precision world data to be fitted by HG et al.

Double-polarized Compton Scattering from a High Pressure Polarized ^{3}He Target at HIGS

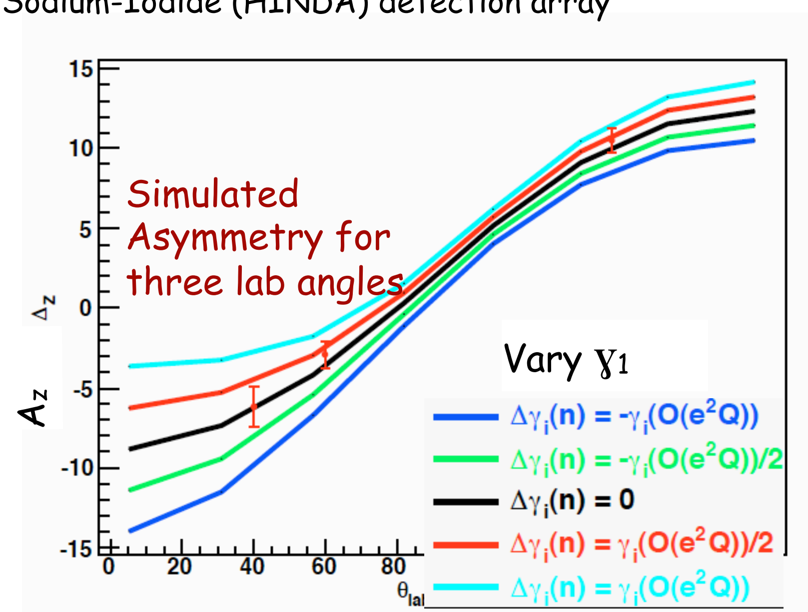
Nucleon structure to QCD ~ Hydrogen atom to QED

Spin polarizabilities provide new information about the structure of the nucleon

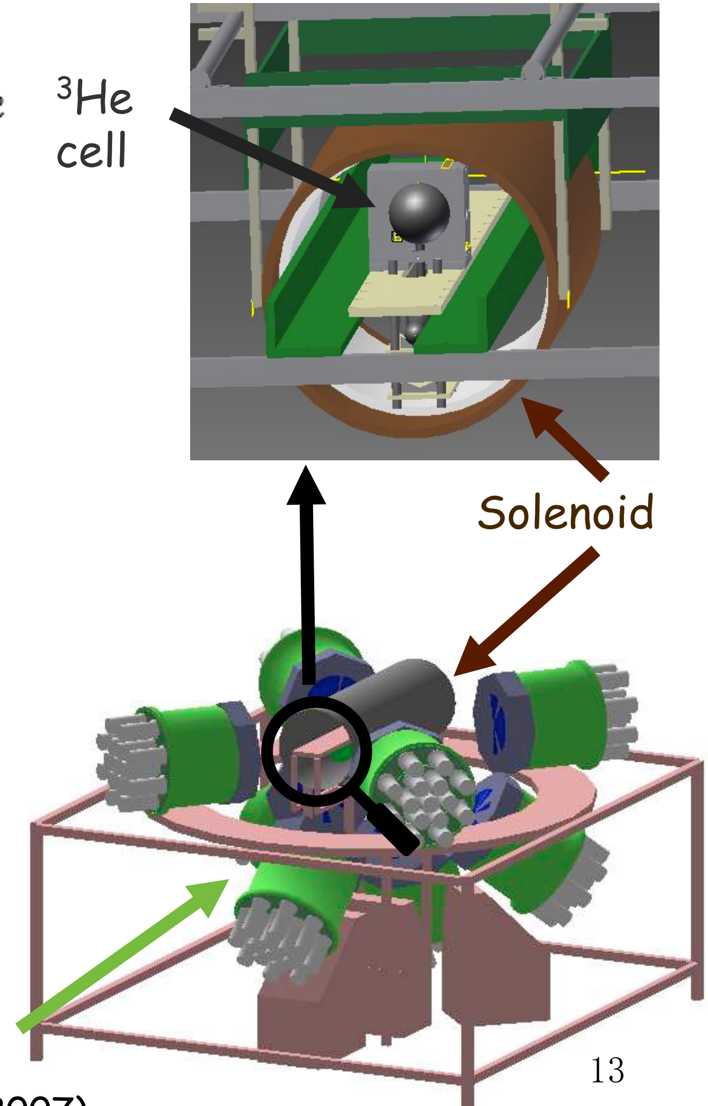
$$\gamma^{\circlearrowleft}\ {}^3\vec{He} \rightarrow \gamma\ {}^3He$$

Extract neutron spin polarizabilities ($\gamma_1, \gamma_2, \gamma_4$) using

- ❖ circularly polarized photon beam at the HIGS facility
- ❖ ^{3}He target polarized in a single-layer solenoid
- ❖ Sodium-Iodide (HINDA) detection array



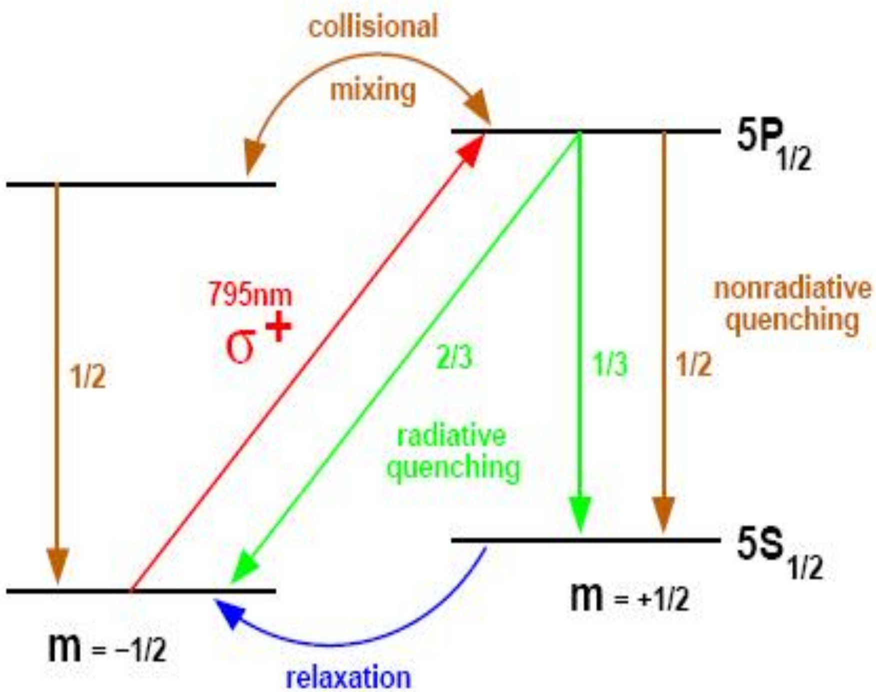
Gao et al.

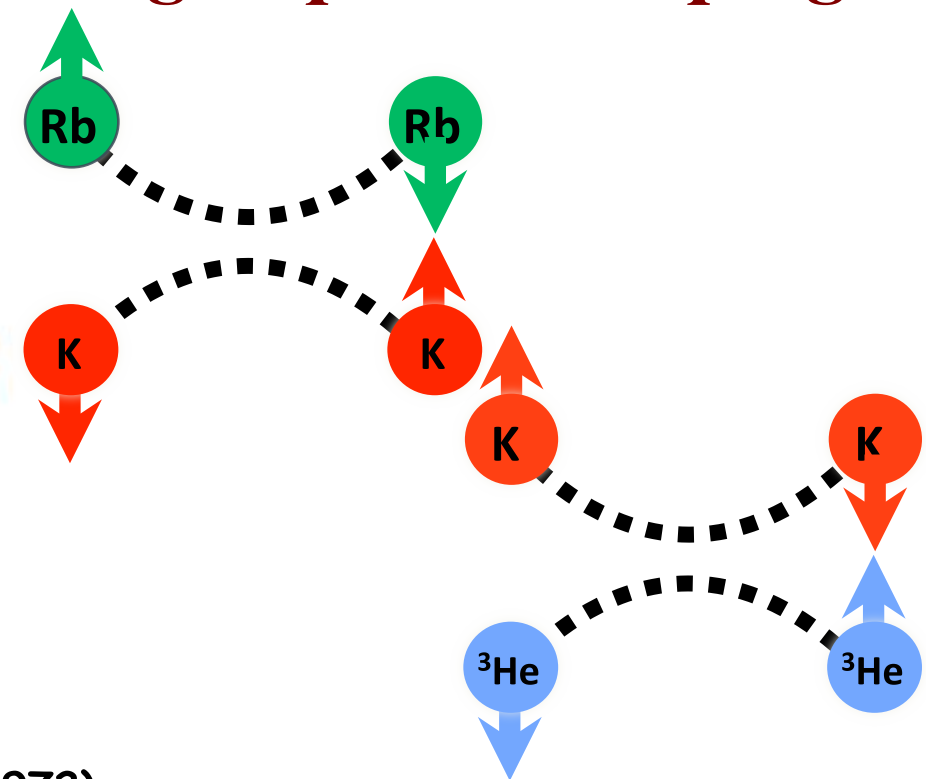


HINDA Array

D. Choudhury, A. Nogga, D. Phillips, Phys. Rev. Lett. 98 232303 (2007)

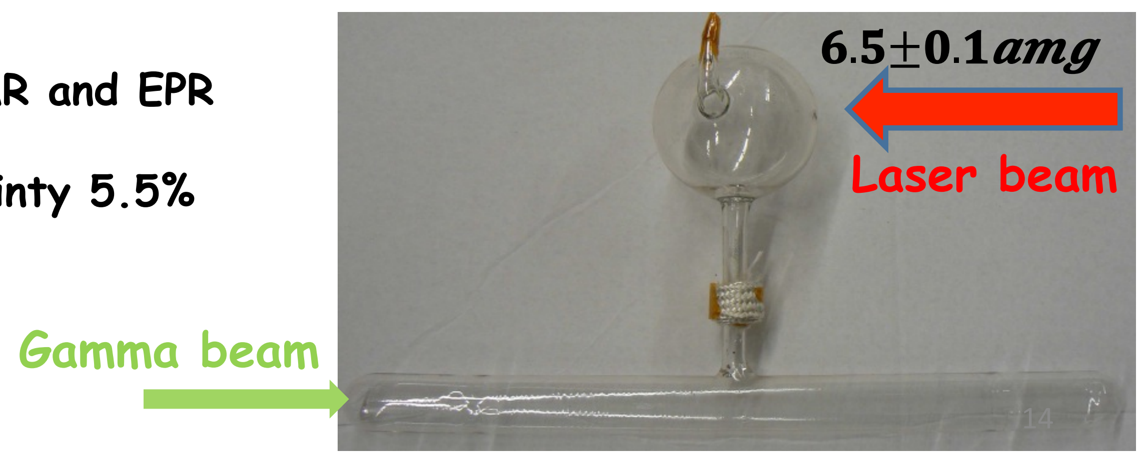
Polarized ^{3}He: Spin Exchange Optical Pumping





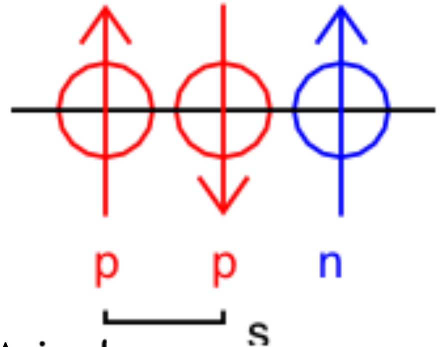
W. Happer, Rev. Mod. Phys. 44, 169 (1972)

- Polarization measured using NMR and EPR
- Polarization: 38-43%
- Polarization systematic uncertainty 5.5%



Test of State-of-the-Art Calculations on ^3He

- Three-nucleon system provides an excellent testing ground of few-body theories
  - e.g. Nuclear corrections on effective neutron target



- Three-body calculations
  - **Deltuva *et al.*** : using AGS equations with CD Bonn + Δ-isobar + **Coulomb potential** +…
  - **Skibiński *et al.*** : using Faddeev equations with AV18+UIX+…
  - Chiral EFT: including one- and two- pion exchange of MEC at NLO
- The advance of theories needs more precise experimental data, new observables

$$H = \sum_i \frac{P_i^2}{2m} + \sum_{i<j} V_{ij} + \sum_{i<j<k} V_{ijk} + \cdots$$

[1] A.Deltuva *et al.*, Phys. Rev. C 71, 054005 (2005); Phys. Rev. C 72, 054004 (2005) and Nucl. Phys. A 790, 344c (2007)
[2] R.Skibinski *et al.*, Phys. Rev. C 67, 054001 (2003); R.Skibinski et al. Phys. Rev. C 72, 044002 (2005)
[3] E.O. Alt *et al.* Nucl. Phys. B2, 167 (1967)
[4] L.D. Faddeev, Sov. Phys. JETP 12 1014 (1961)
[5] R. Rozpedzik *et al.* , Phys. Rev. C 83, 064004 (2001)

Investigation of the GDH Sum Rule

S.B.Gerasimov in Sov. J. Nucl. Phys.; S.D. Drell *et al.*, in Phys. Rev. Lett. (1966)

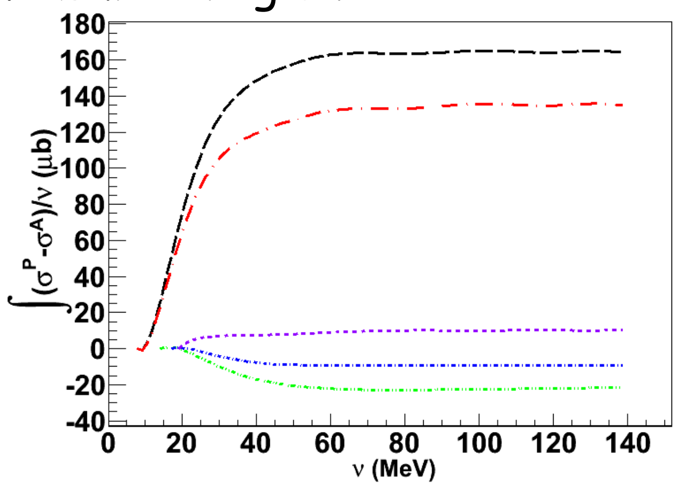
$$I^{GDH} = \int_{\nu_{thr}}^{\infty} \frac{d\nu}{\nu}\left[\sigma_N^P(\nu) - \sigma_N^A(\nu)\right] = \frac{4\pi^2\alpha}{M_N^2}\kappa_N^2 I$$

σ_N^P σ_N^A spin dependent total photon-absorption cross section
κ_N anomalous magnetic moment
ν_{thr} pion production/photodisintegration threshold

Based on general principles of physics: **Lorentz and gauge invariance, crossing symmetry, causality and unitarity**

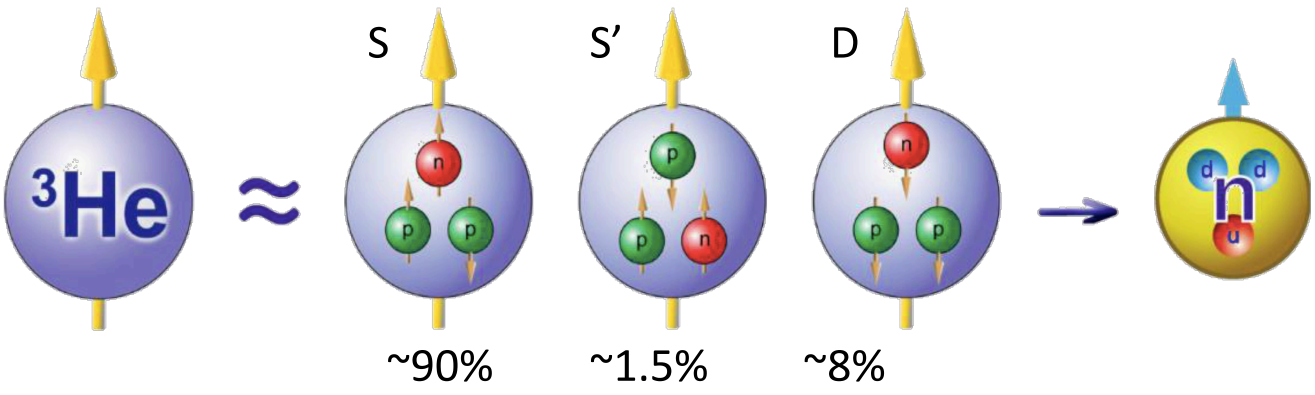
Measurements on proton up to 0.8 GeV (Mainz, MAMI) and up to 2.9 GeV (Bonn, ELSA) and on neutron between 0.8 GeV and 1.8 GeV (Bonn, ELSA) agree with GDH within assumptions for contributions from un-measured region

Plateau value of the GDH integral of ^{3}He below pion threshold based on state-of-the-art calculations is ~140μb.
Total $I^{GDH,^3He}$=496 μb



K. Helbing, Progress in Particle and Nuclear Physics **57**, 405 (2006)

Photodisintegration of ^{3}He with double polarizations at HIγS at TUNL



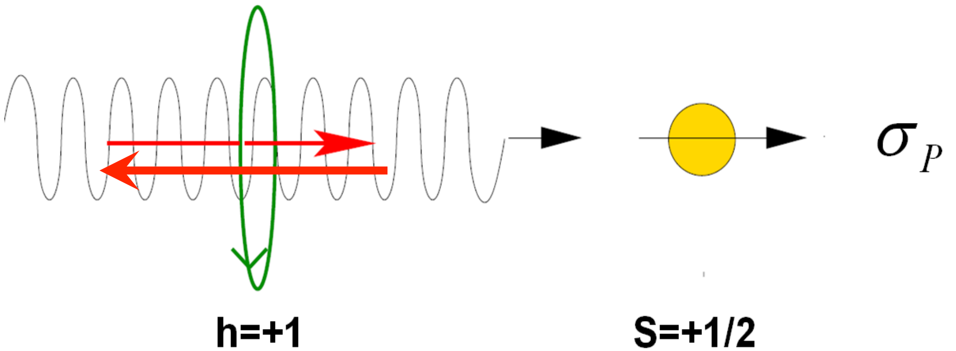
Two-Body Breakup $\gamma + {}^3He \rightarrow p + d$

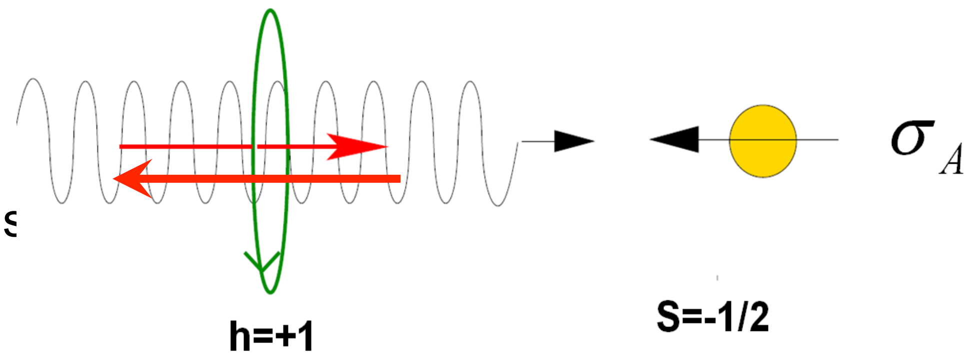
Three-Body Breakup $\gamma + {}^3He \rightarrow p + p + n$

Experimental Overview

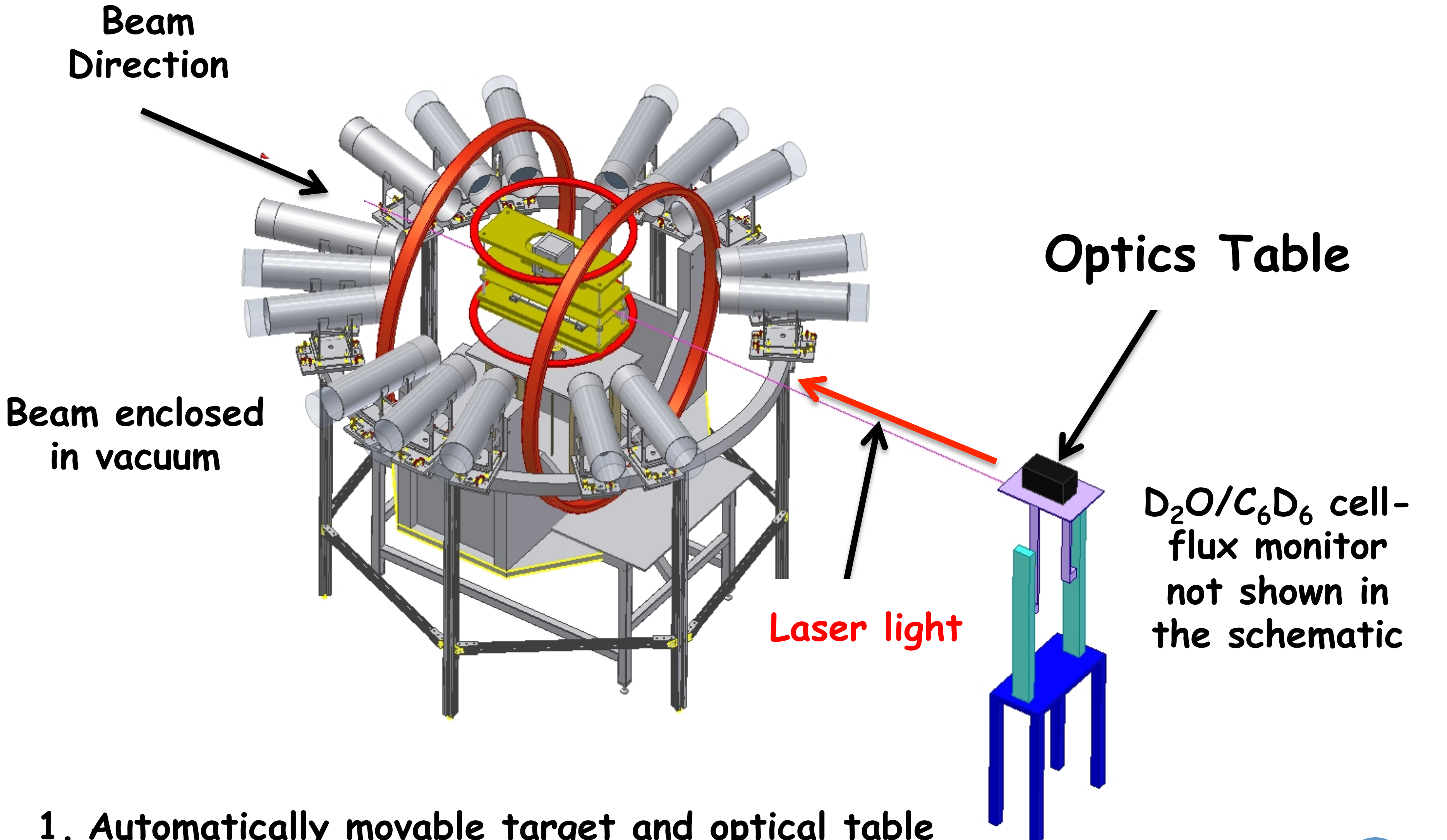
Break up channel $\vec{\gamma} + \overrightarrow{{}^3He} \rightarrow p + p + n$

- ~100% circularly polarized γ-beam at 12.8, 14.7, and 16.5 MeV
- Neutrons detected with 16 neutron detectors at different angles
- High pressure hybrid ^{3}He target (~7amgs) polarized longitudinally using Spin Exchange Optical Pumping
- Polarized ^{3}He target spin slip @ 15 mins



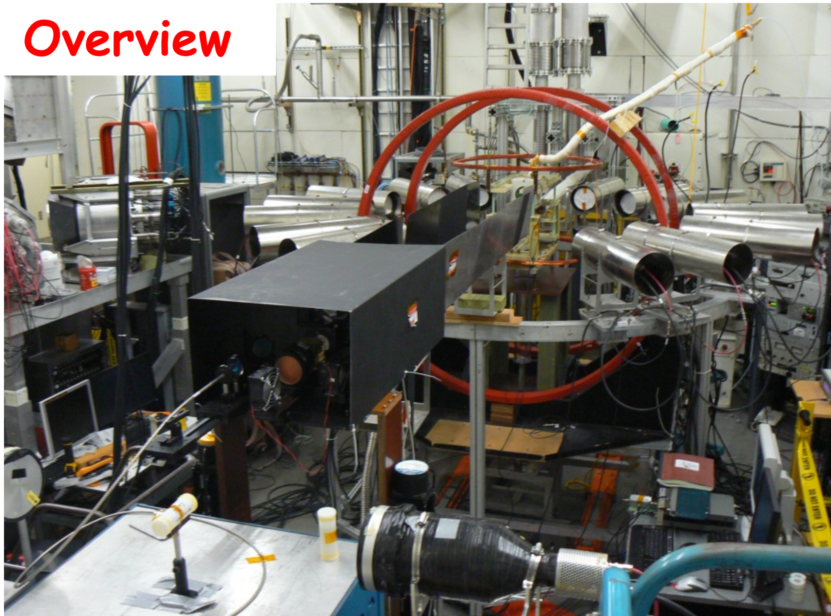


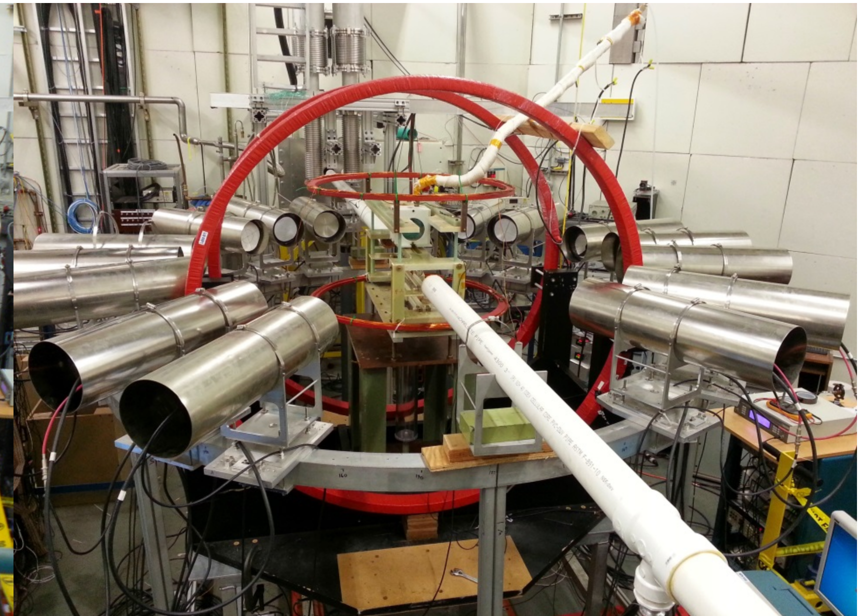
Experimental setup

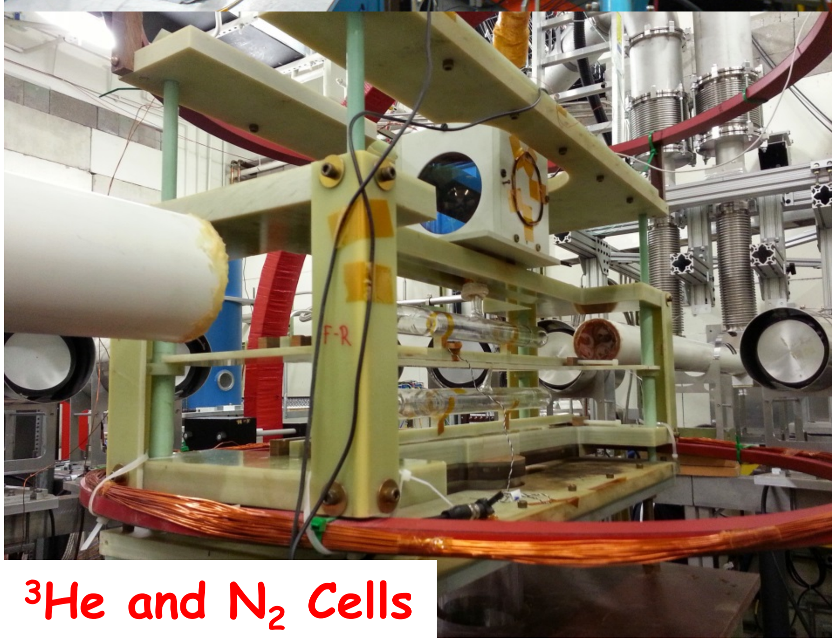


1. Automatically movable target and optical table
2. Detectors in mu-metal shielding tubes

Overview



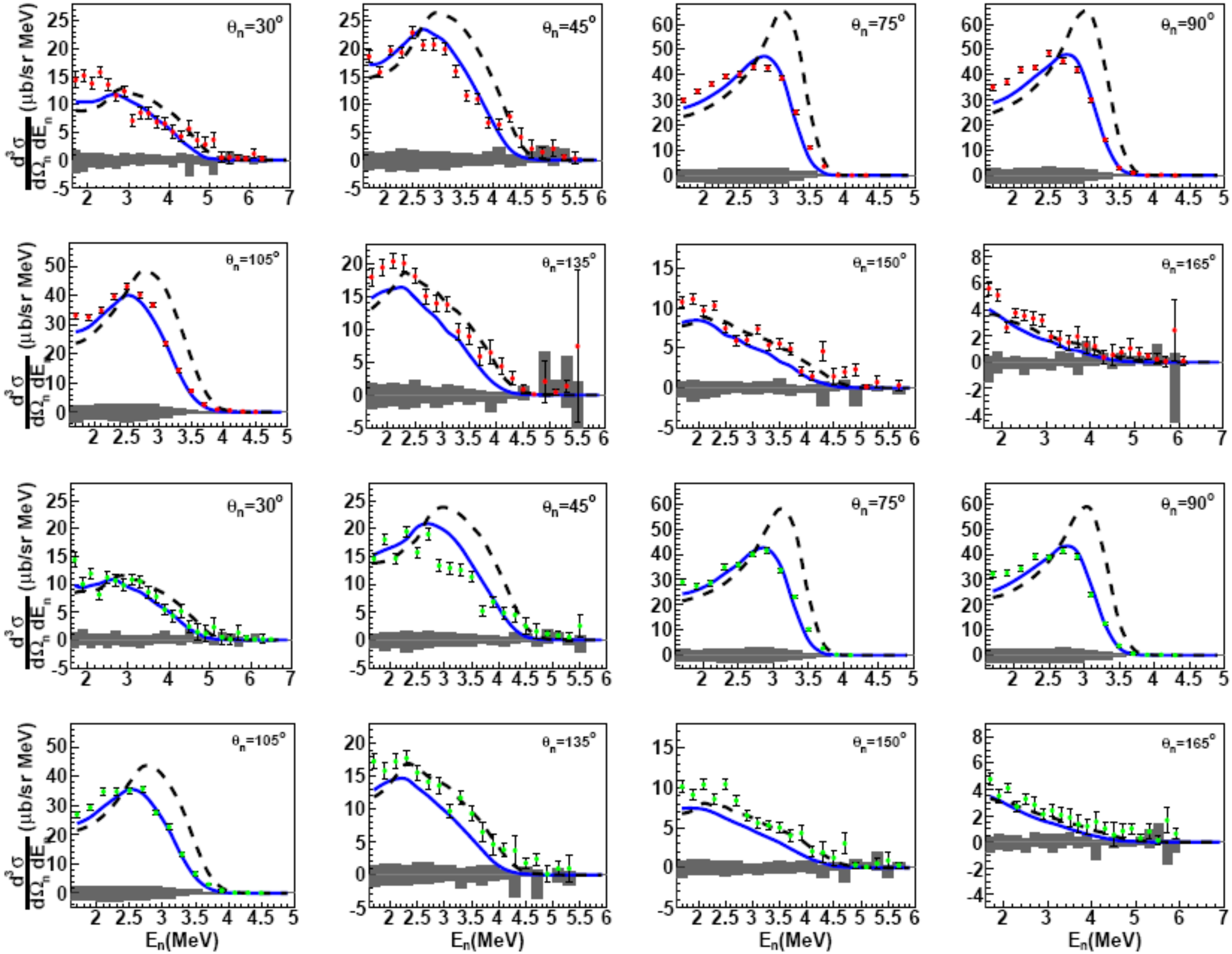




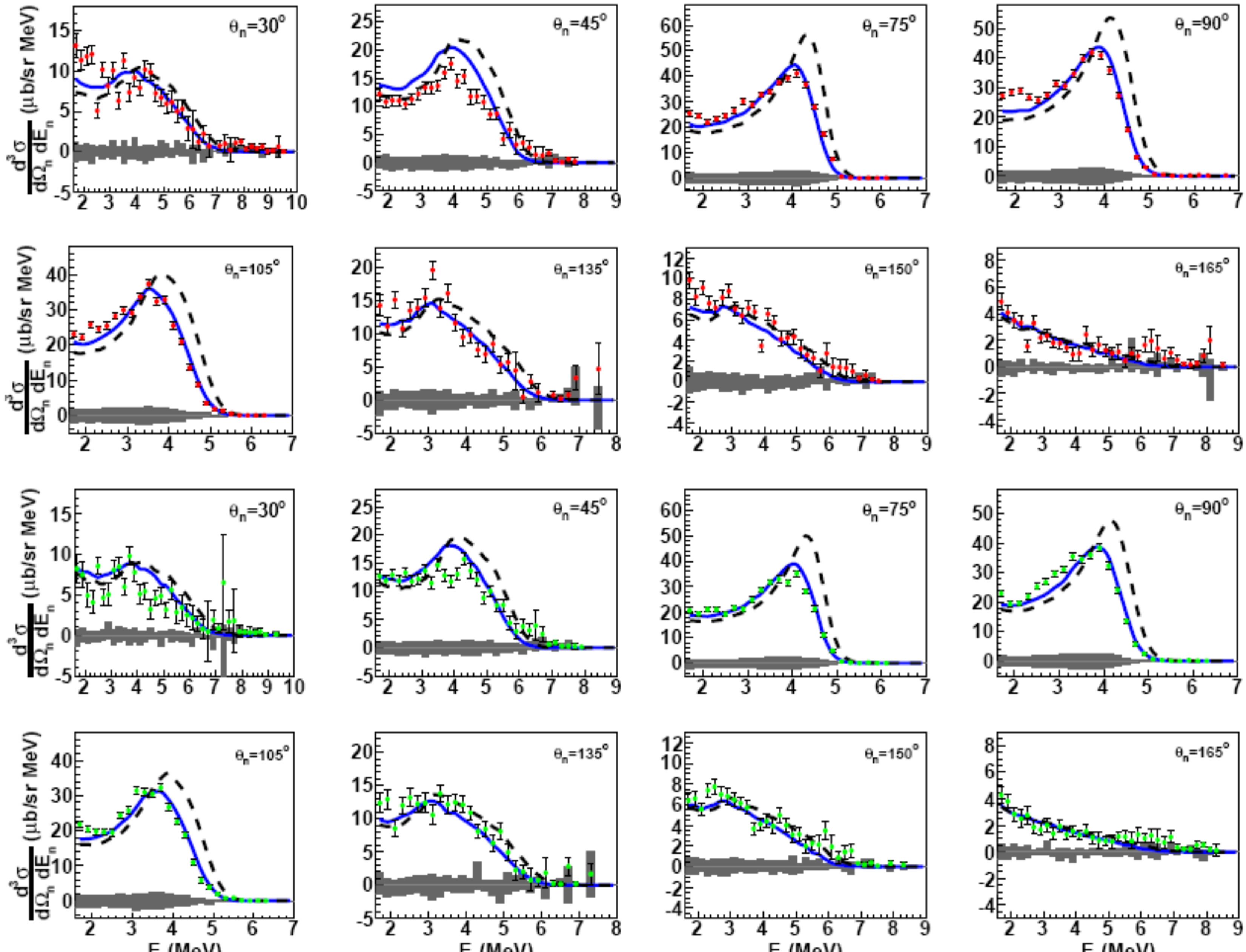
^{3}He and N_2 Cells

Front and Back Vacuum Pipes

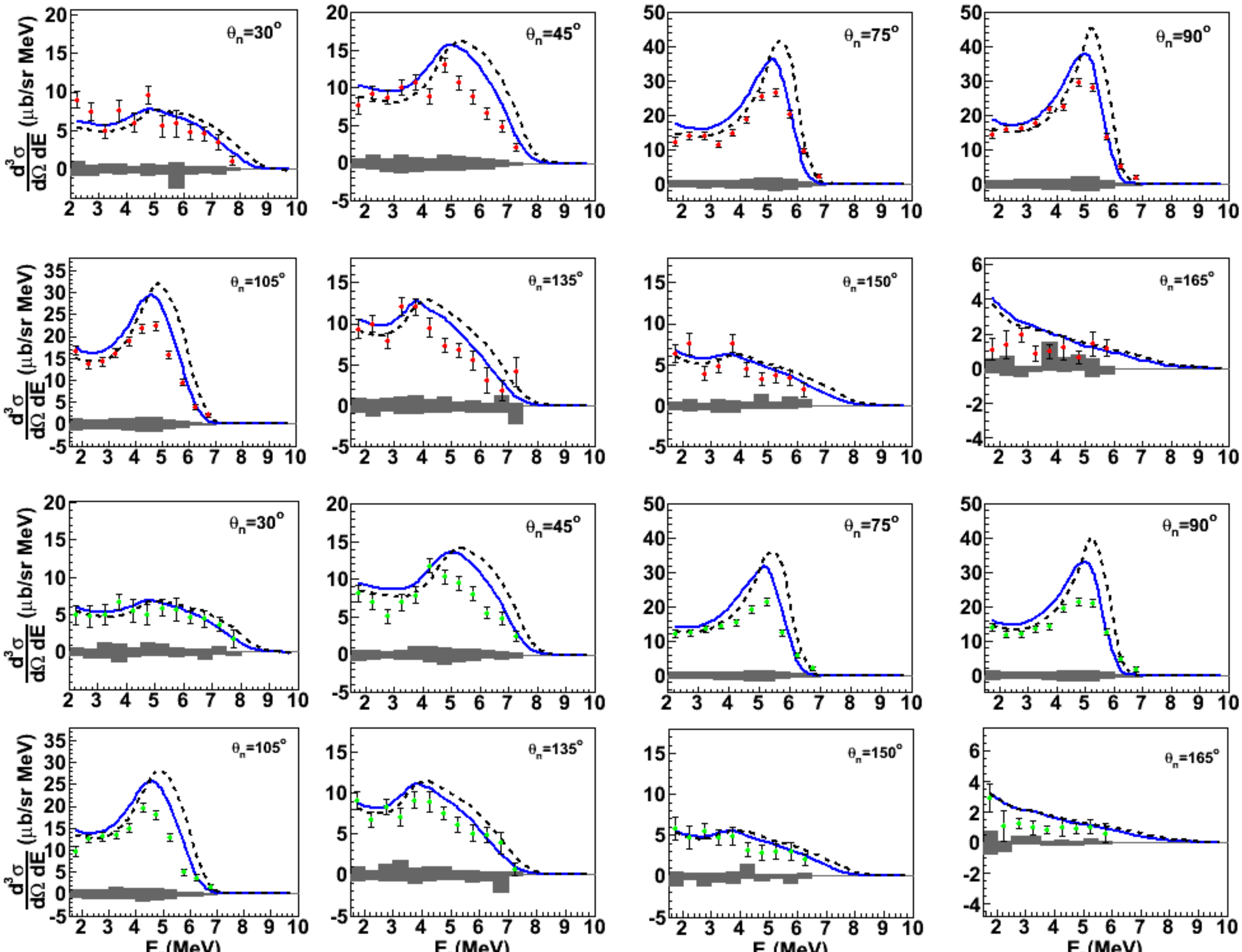
Spin-Dependent Double Differential Cross Sections at 12.8 MeV compared with Deltuva and Skibinski et al. calculations



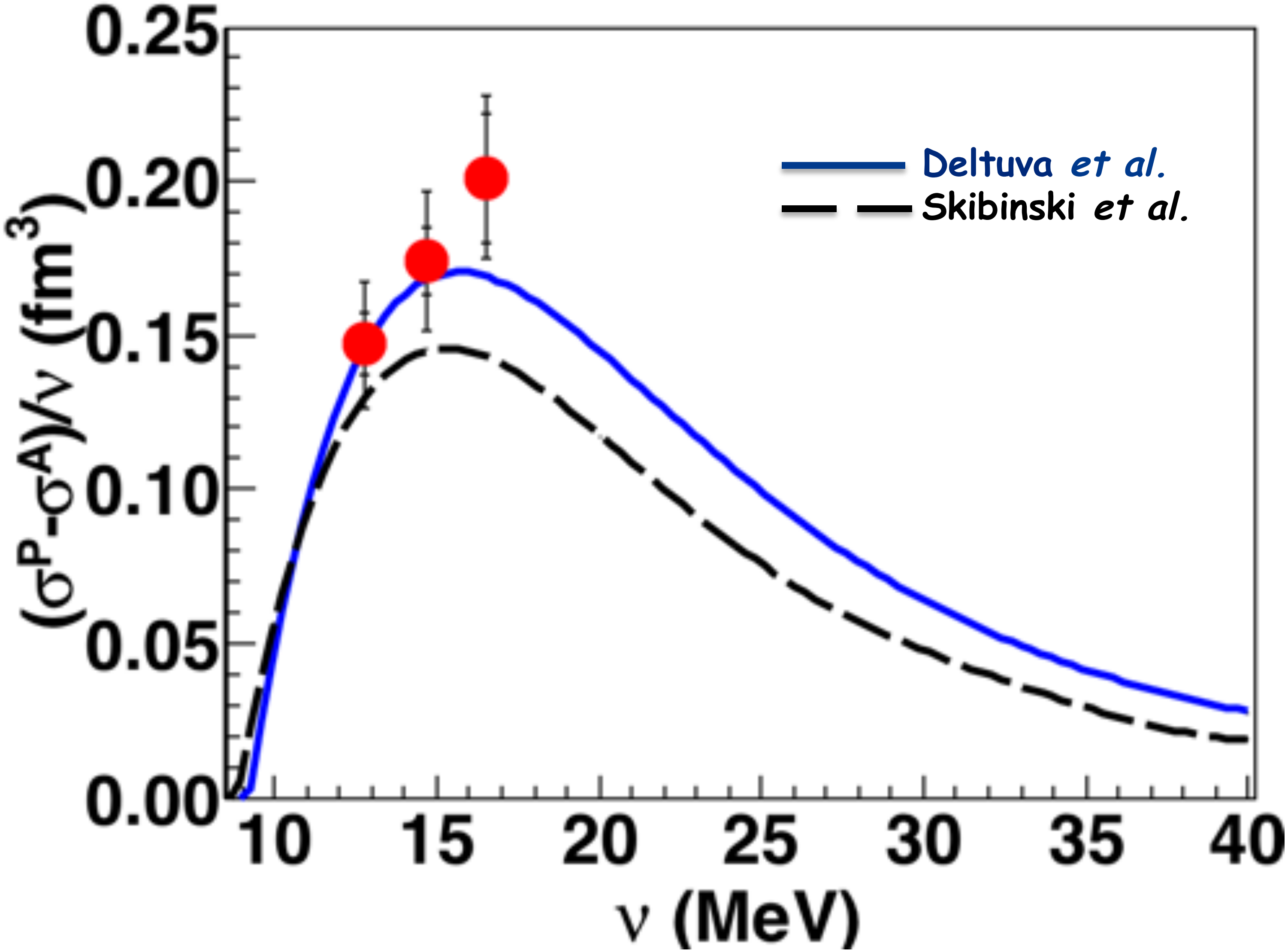
Spin-Dependent Double Differential Cross Sections at 14.7 MeV



Spin-Dependent Double Differential Cross Sections at 16.5 MeV



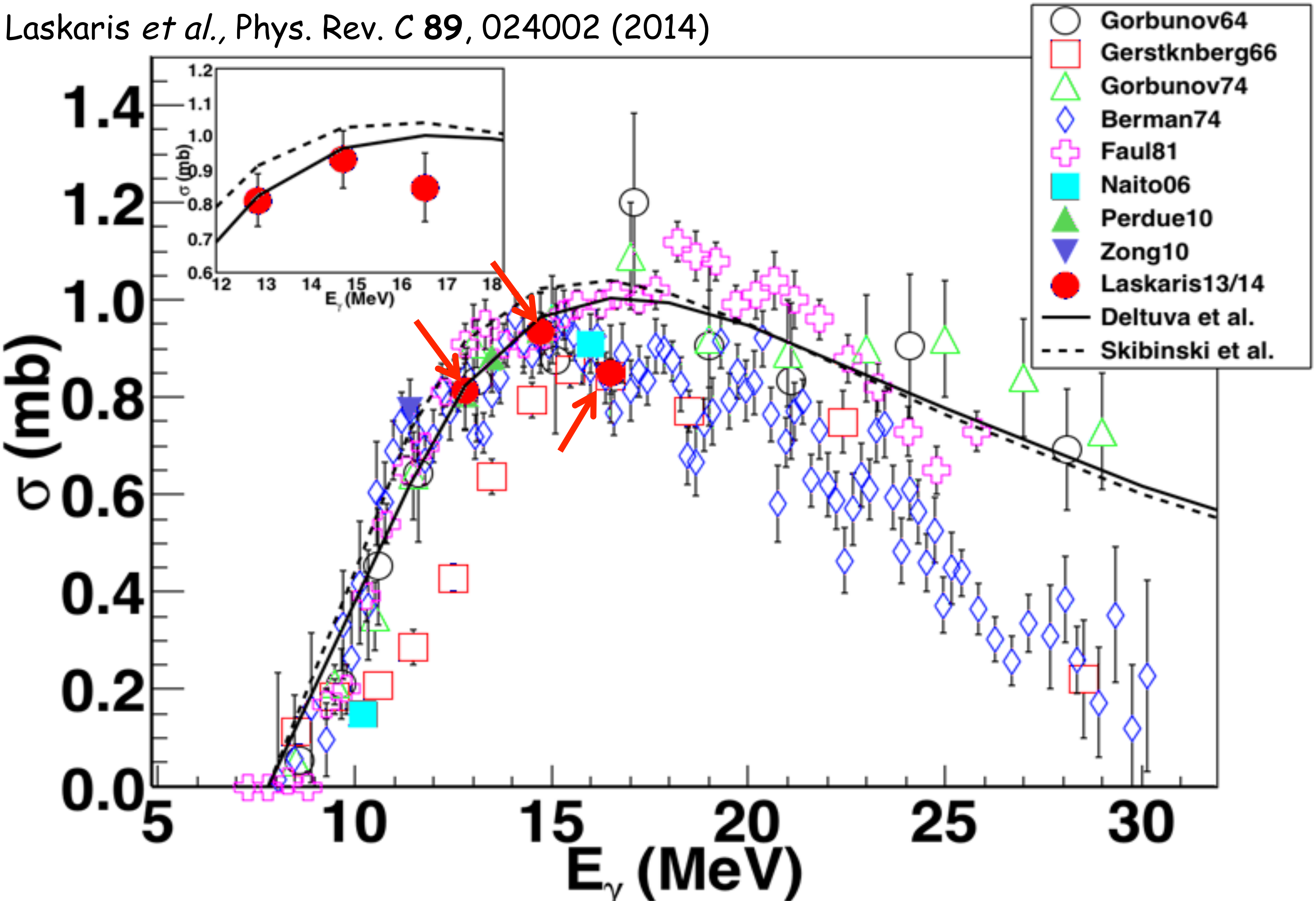
Contribution to ^{3}He GDH integrand



G. Laskaris *et al.*, Phys. Rev. Lett. **110**, 202501 (2013)
G. Laskaris *et al.*,Three-body break-up of ^{3}He with double polarizations at 16.5 MeV (2014)

Total Cross Sections for $^3He(\gamma,n)pp$

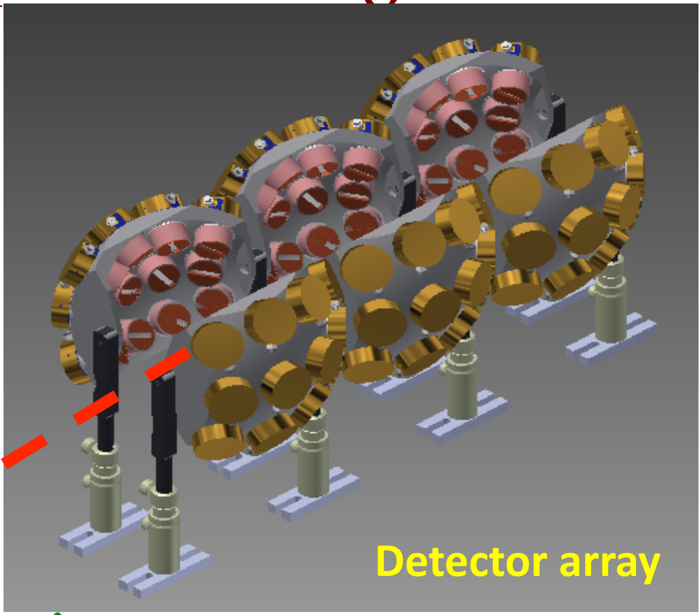
G. Laskaris *et al.*, Phys. Rev. *C* **89**, 024002 (2014)

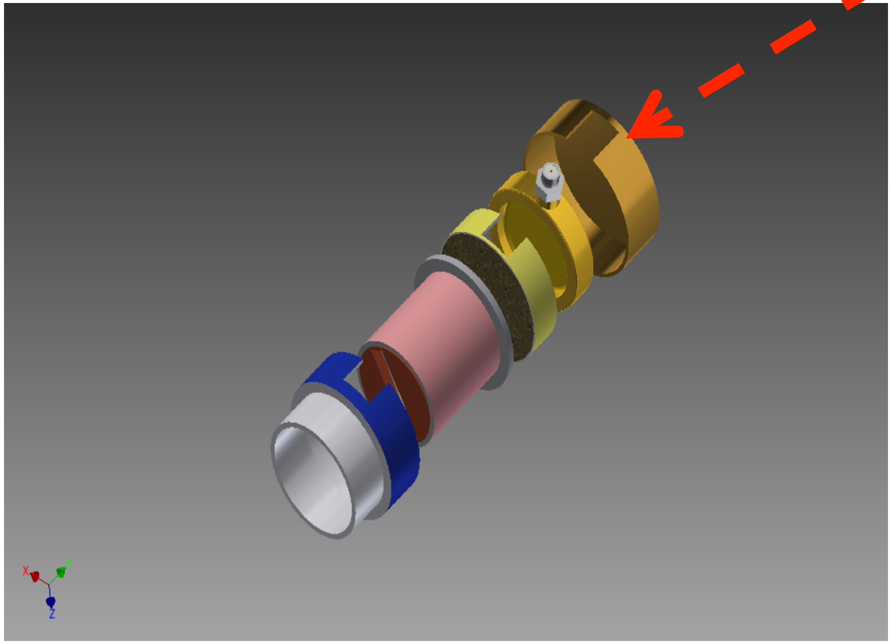


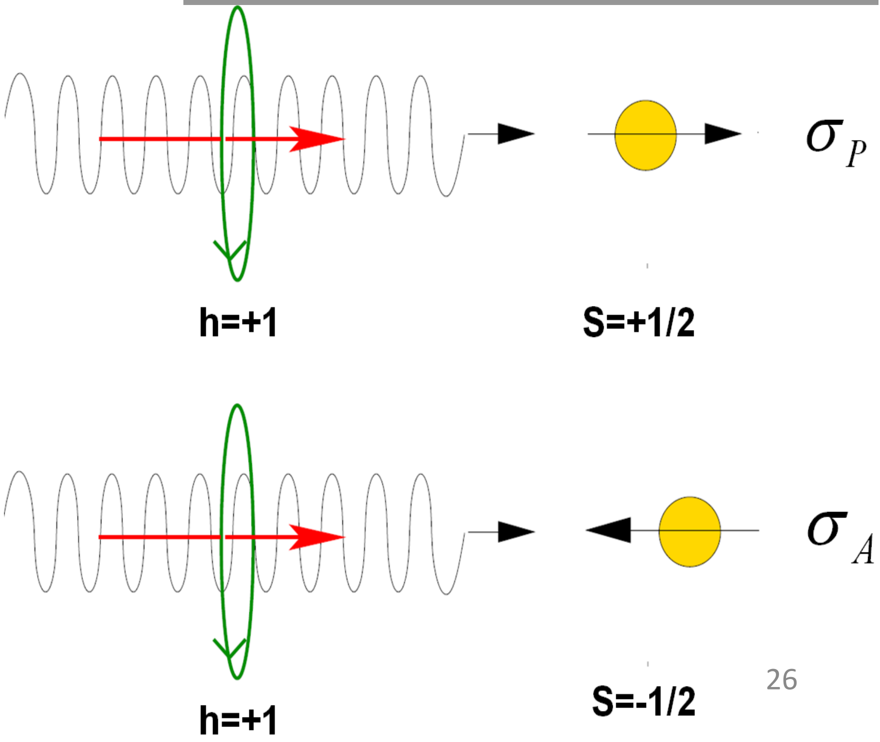
G. Laskaris *et al.*,Three-body break-up of ^{3}He with double polarizations at 16.5 MeV (2014)

Experimental Overview on two-body photodisintegration

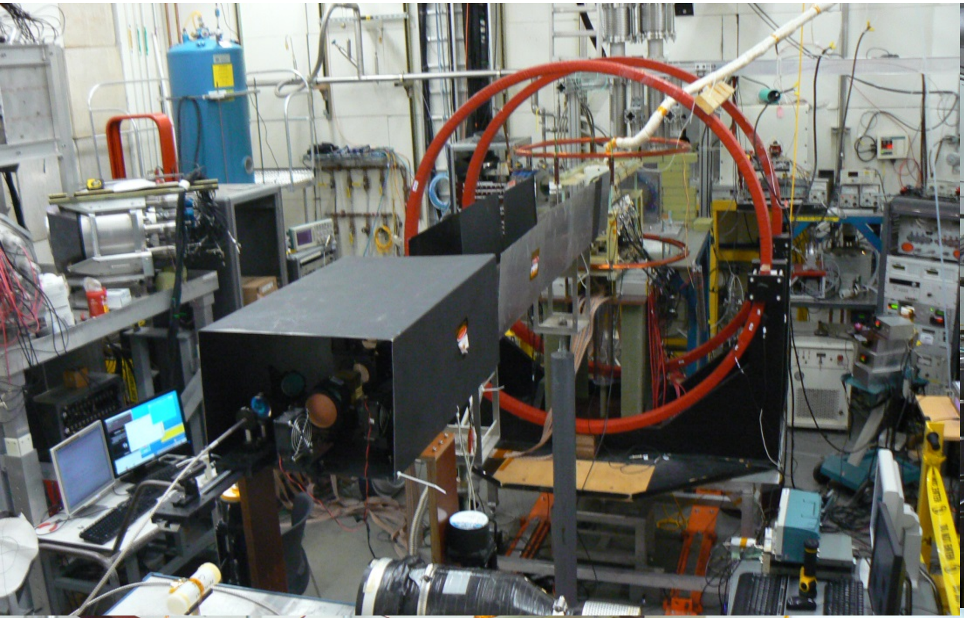
- ~100% circularly polarized γ-ray
- Polarized ^{3}He target, spin flip every 15 min
- Detect Protons using 72 SSB Detectors 300-500μm thick, 450 mm^2 at 45°, 70°, 95° and 120° (18 detectors per angle)
- 142 hrs on ^{3}He cell and 58 hrs on N_2 reference cell

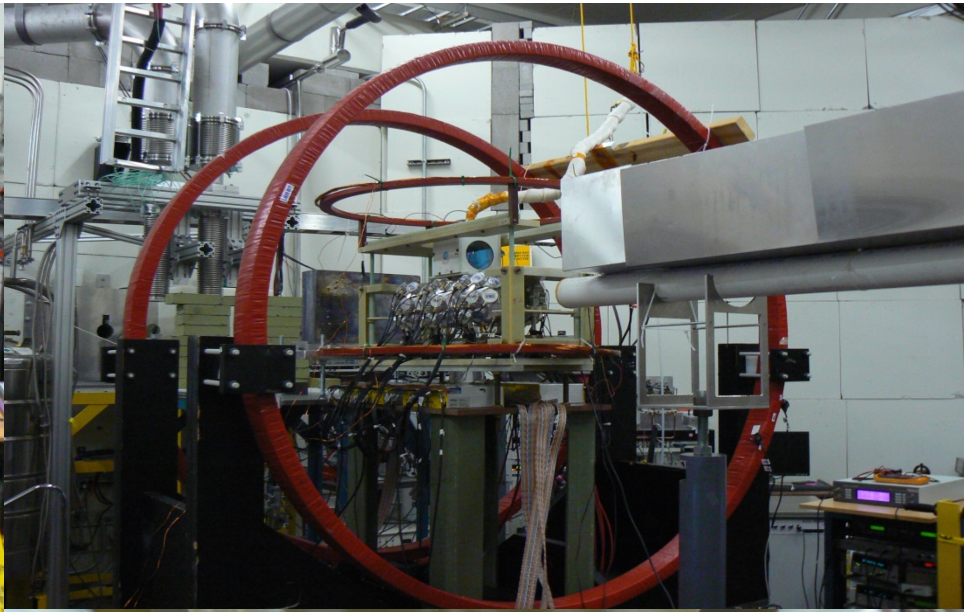




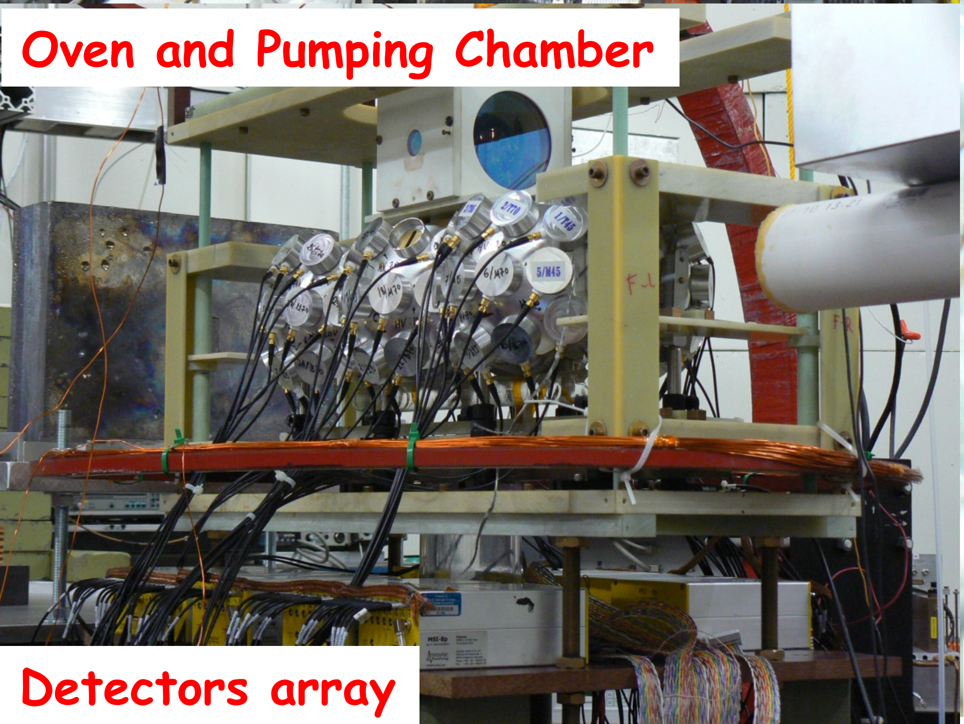


Experimental Apparatus

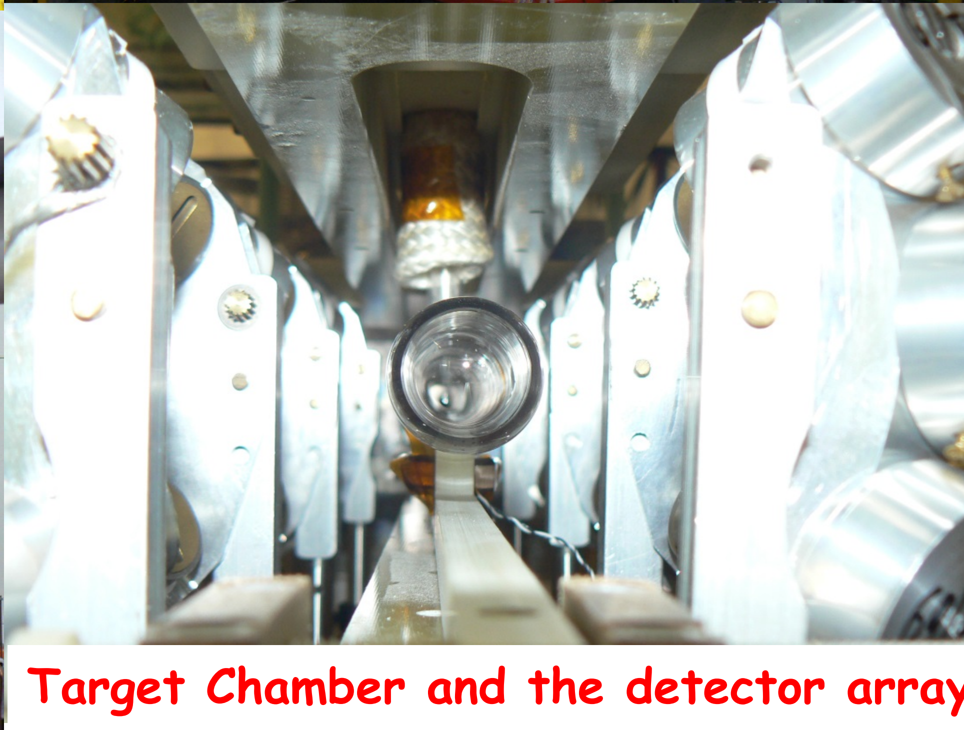




Oven and Pumping Chamber

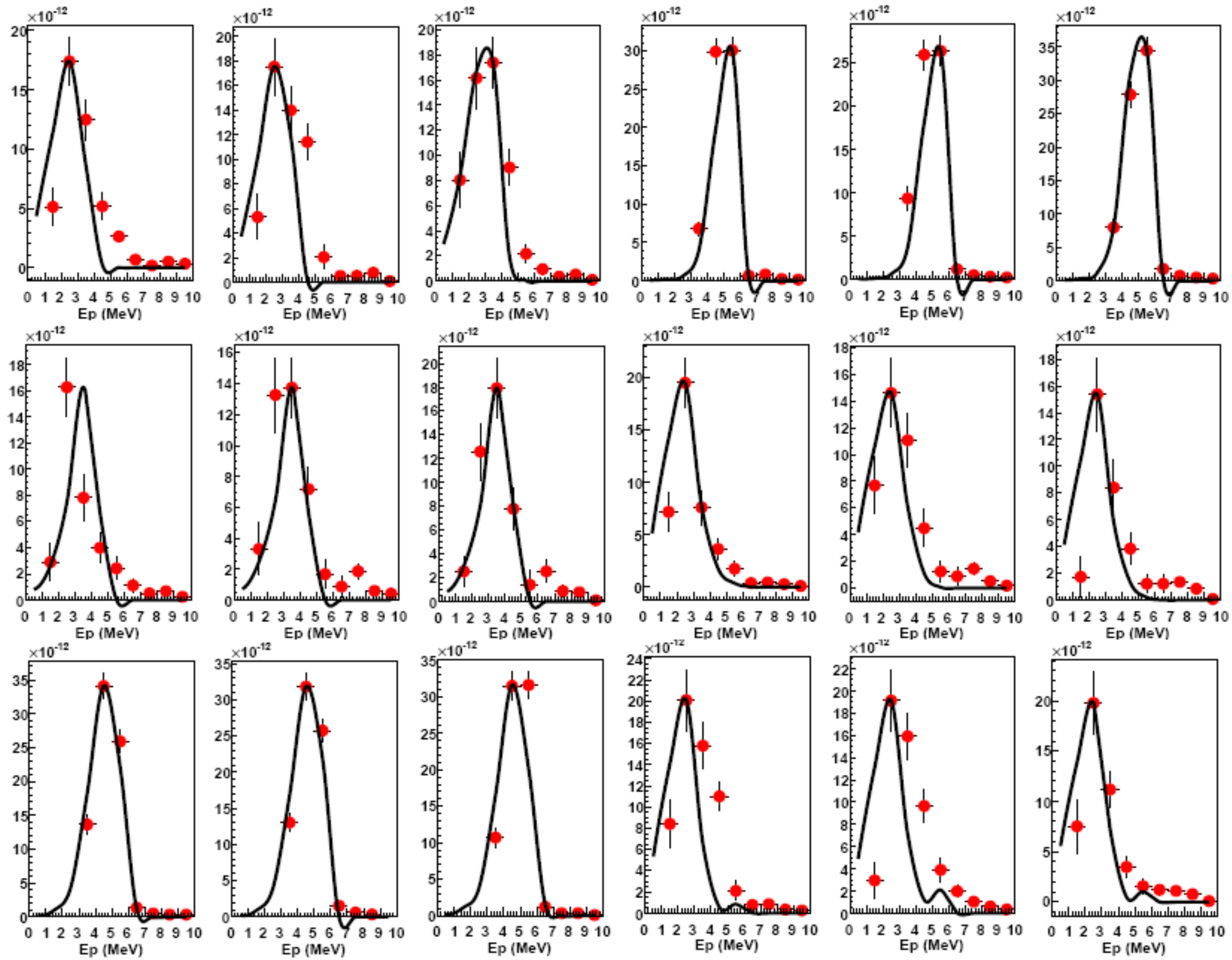


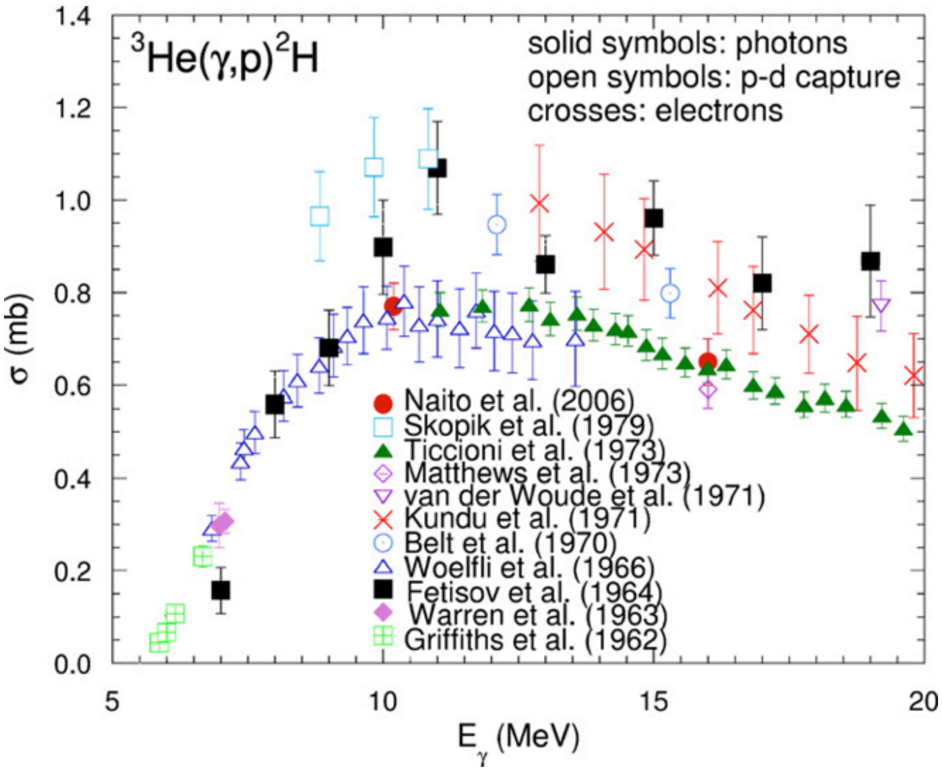
Detectors array

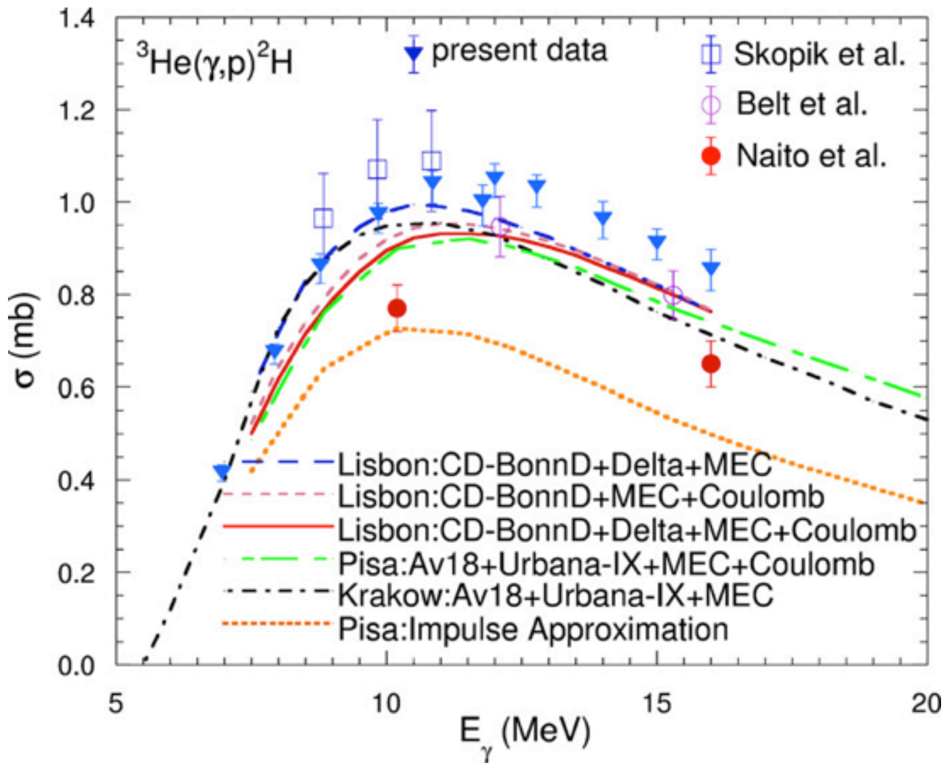


Target Chamber and the detector array

Comparison of yields: ^{3}He vs theory,95^{o}







from W. Tornow et al., Phys. Lett. B 702, 121 (2011)

GDH Measurements on the Deuteron

HIFROST – HIGS FROzen Spin Target

B. Norum et al.

$^3He/^4He$ Dilution refrigerator originally obtained from Geesthacht, Germany

d-Butanol 10 cm target

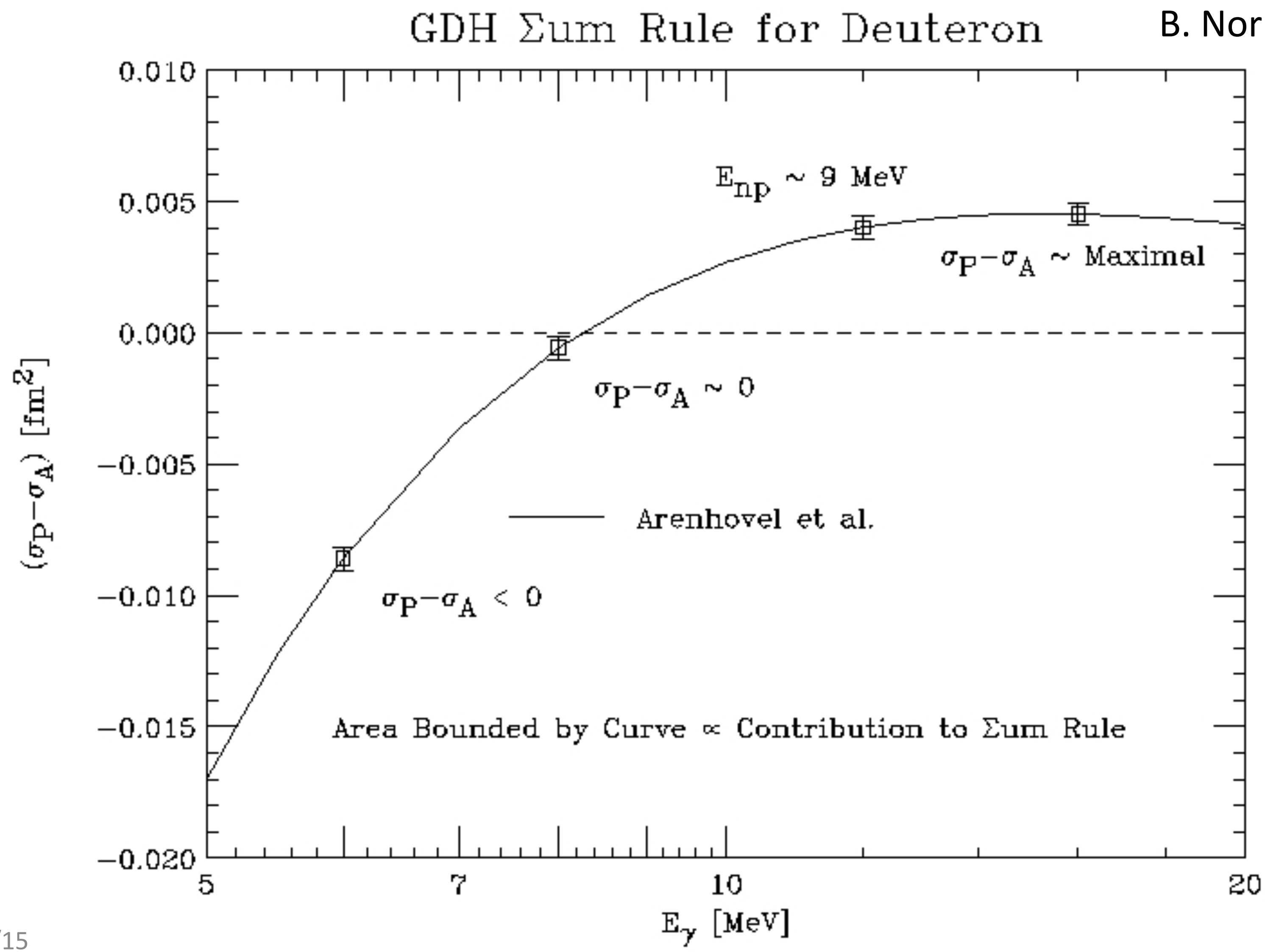
Assembled and initially tested at UVA

Currently being installed at HIGS

Technical lead – Don Crabb (UVA)

GDH Measurements on the Deuteron (projected)

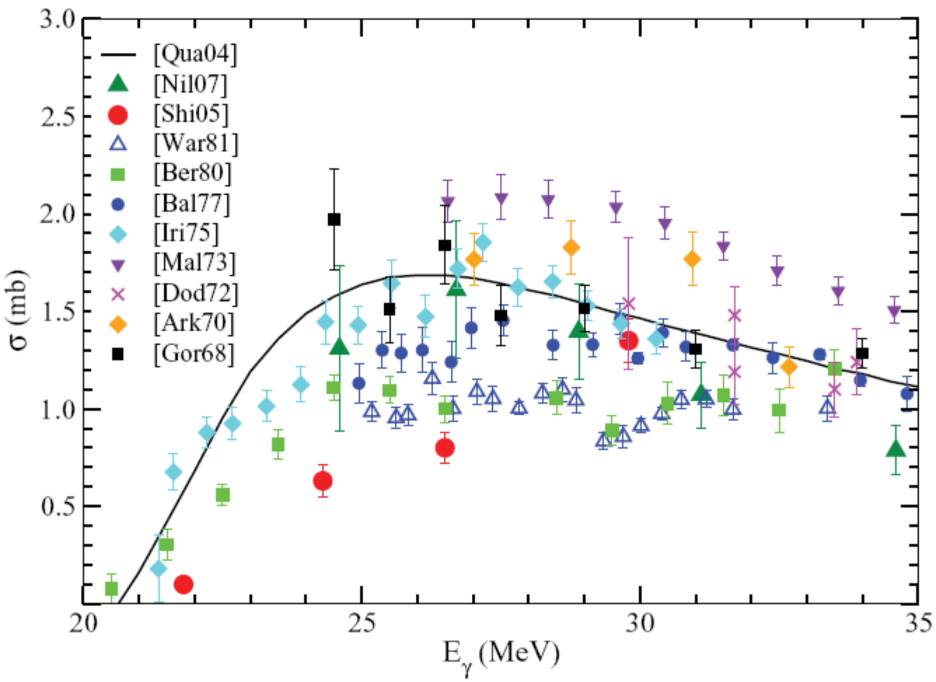
B. Norum et al.

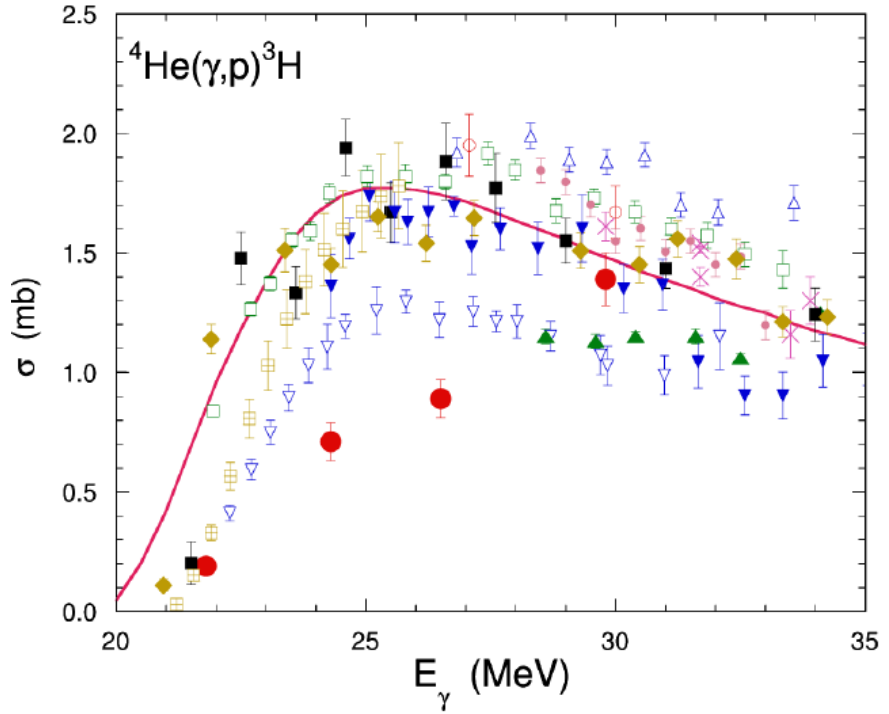


The Few-Body System: ^{4}He Inconsistencies !

World Data on

$^4He(\gamma,n)^3He$ — $^4He(\gamma,p)^3H$





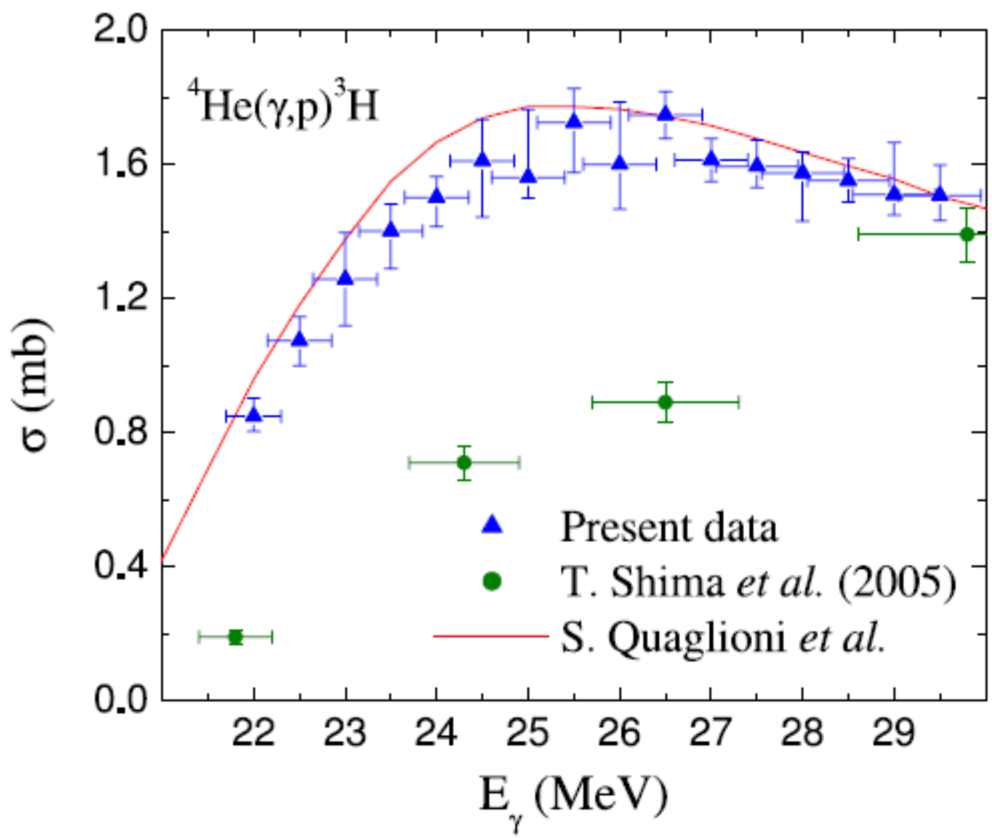
References: Raut *et al.*, PRL, 108, 042502 (2012), and Tornow *et al.,* PR C85, 061001R (2012)

The Few-Body System: ^{4}He Results from HIGS

PRL **108,** 042502 (2012) PHYSICAL REVIEW LETTERS week ending 27 JANUARY 2012

Photodisintegration Cross Section of the Reaction $^4He(\gamma, p)^3H$ between 22 and 30 MeV

R. Raut,[1,2,*] W. Tornow,[1,2] M. W. Ahmed,[1,2,3] A. S. Crowell,[1,2] J. H. Kelley,[4,2] G. Rusev,[1,2]
S. C. Stave,[1,2] and A. P. Tonchev[1,2]



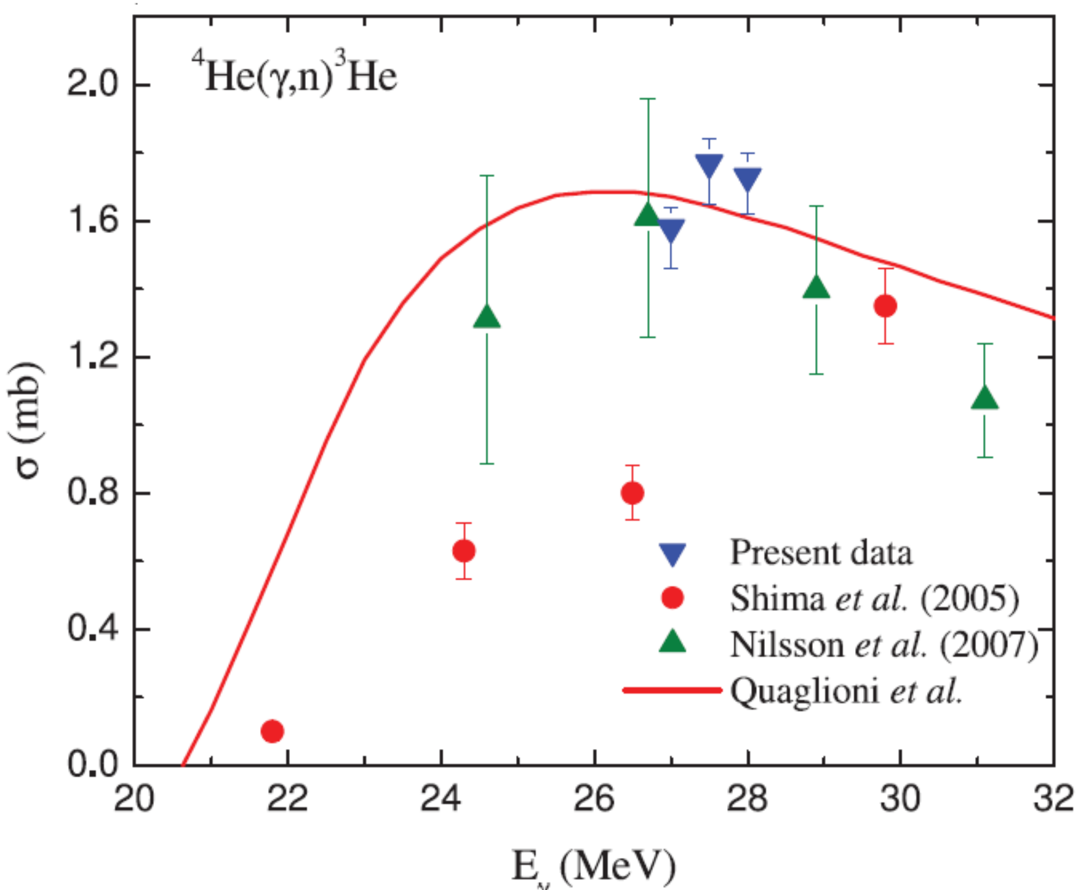
The Few-Body System: ^{4}He Results from HIGS

RAPID COMMUNICATIONS

PHYSICAL REVIEW C **85**, 061001(R) (2012)

Photodisintegration cross section of the reaction $^4He(\gamma,n)^3He$ at the giant dipole resonance peak

W. Tornow,[1,2] J. H. Kelley,[3,2] R. Raut,[1,2,*] G. Rusev,[1,2,†] A. P. Tonchev,[1,2,‡] M. W. Ahmed,[1,2,4]
A. S. Crowell,[1,2] and S. C. Stave[1,2,§]



Differential cross-section measurements of two- and three-body photodisintegration of triton

Collaboration: C.R. Howell (spokesperson), A.S. Crowell, L.C. Cumberbatch, B. Fallin, , F.Q.L. Friesen, D. Ticehurst, W. Tornow Duke Univ. and TUNL; M.W. Ahmed, B.J. Crowe (North Carolina Central Univ. and TUNL)

Measurement at HIγS; E_γ = 15 and 25 MeV

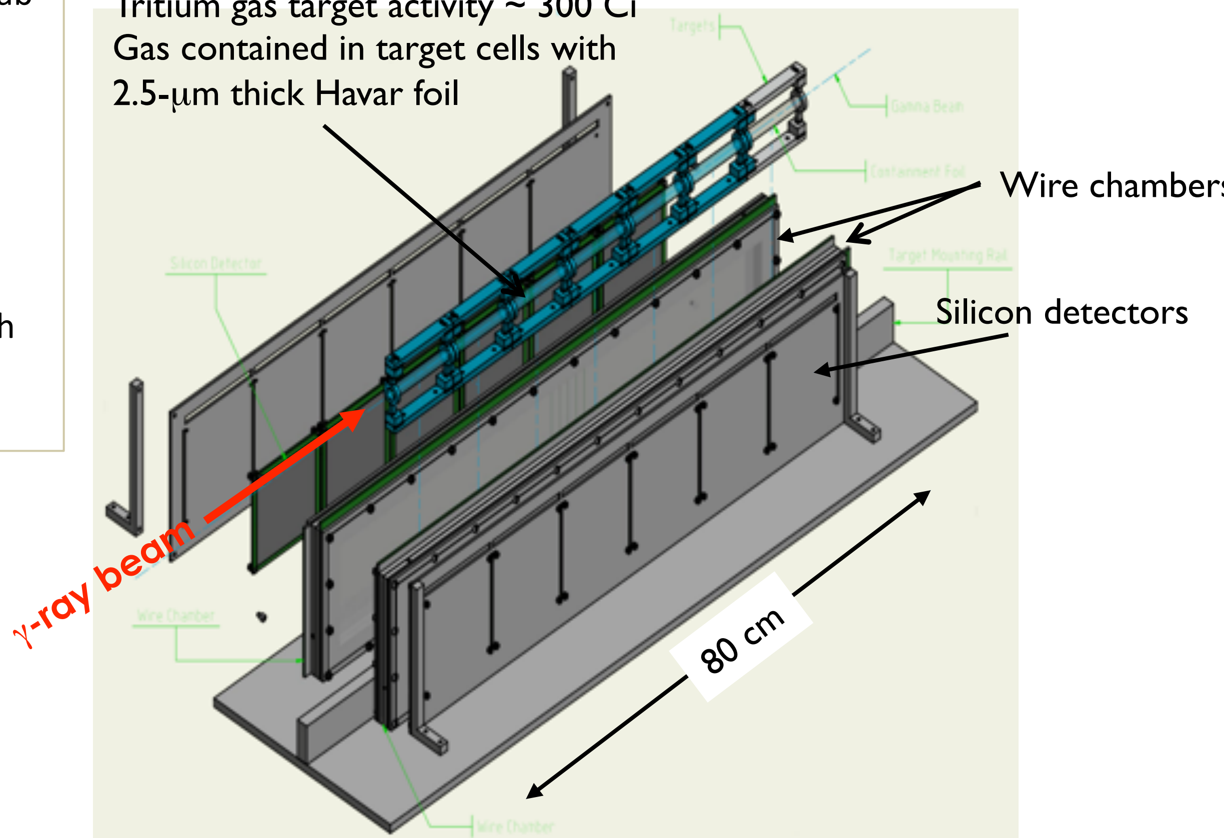
Goals:

1. Provide data to develop and test ab-initio 3N calculations:
   - First differential cross-section measurements for this reaction
   - Data for isospin partner of 3He
   - No Coulomb interaction
2. First determination of the $^1S_0$ neutron-neutron scattering length

C. Howell et al.

Experiment setup: measure momentum of emitted protons and deuterons

Tritium gas target activity ~ 300 Ci
Gas contained in target cells with 2.5-μm thick Havar foil



Summary and outlook

- HIγS facility with high-intensity flux and polarizations provides great opportunities for Compton scattering – important contributions to structure of the nucleon
- Great results coming out/will be related to GDH sum rule for deuteron and ^{3}He
- New, precision data from few-body processes provide stringent test of state-of-the-arts few-body calculations and clarify experimental situations
- Stay tuned for new results from HIγS

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